FINAL REPORT

Converting Constant Volume, Multizone Air Handling Systems to Energy Efficient Variable Air Volume Multizone Systems

Energy and Water Projects
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EXECUTIVE SUMMARY

A low-cost cost technique to retrofit a constant volume multizone system to a more energy efficient variable volume system was demonstrated on five systems at Fort Bragg, NC and ERDC-CERL, in Champaign IL. When starting with a constant volume multizone air handler with modern direct digital controls (DDC), this conversion requires programming changes to the control strategy executed by the control system as well as the installation of an air flow measurement array (AFMA) and variable frequency drives for the supply and return fans (if so equipped). A key feature of this approach is that the physical system is only minimally affected, and except for the location at which the AFMA is installed the ductwork is not modified.

The updated control strategy varies the fan speeds based on the zone demand as determined by zone damper position, minimizing the fan energy used as well as the cooling and heating energy required to maintain occupant comfort by reducing the amount of simultaneous heating and cooling that occurs in a zone. Heating and cooling energy savings are most pronounced in traditional multizone systems with a hot deck and cold deck that operate simultaneously, but are also realized in systems with a neutral deck.

The five demonstration systems were retrofitted and operated for a period of approximately one year, alternating between three test modes. Test mode 0 simulated the pre-retrofit condition and operated the system as a constant volume multizone with a fixed outside air damper position. Test modes 1 and 2 employed variable volume control strategies. Test mode 1 operated with a fixed outside air flow setpoint, and test mode 2 introduced demand controlled ventilation schemes for determining the outside air flow setpoint. Additional instrumentation including BTU and electric meters was installed on the demonstration system at the time of retrofit to provide data for analysis of system performance. The existing utility monitoring and control systems (UMCS[1]) were used to log data from the system throughout the demonstration period.

The five systems were analyzed for energy savings, life cycle cost, occupant thermal comfort and maintainability, where each of these factors were compared to the baseline constant-volume system.

> *Energy Savings:* All systems easily met the energy savings goals of 10% energy use reduction, with energy reduction ranging from 24%-60%.
>
> *Life Cycle Cost:* One of the five systems met the life cycle cost goals of a 3-year payback period assuming the conversion is added to an existing DDC system or planned renovation ("incremental retrofit") and 10-year payback for the complete renovation of a system from non-DDC to DDC with variable volume control. Three other systems had longer payback periods less than the system life for the incremental retrofit, however, demonstrating that the addition of variable volume control to a DDC retrofit is still economical in those cases. Since retrofit costs are relatively static across system sizes, the long payback periods for smaller systems can be expected and demonstrates that some care should be exercised in selecting appropriate systems on which to apply this technique.
>
> *Thermal Comfort:* The two systems at CERL performed nearly the same across all three operating modes. The difference across modes was more significant at Fort Bragg, where 2 had worse comfort performance in the variable volume modes, where one system spent 29-33% of time within the thermal comfort range in modes 1 and 2 versus 39% of time the time for mode 0, and the other system spending 55% of the time in the comfort range in modes 1 and 2 versus 61% in

[1] A utility monitoring and control system (UMCS) is a basewide control system including one or more building control systems and a front end which provides a user interface and supervisory functions such as scheduling, alarming, and trending.

mode 0. The third system at Fort Bragg performed significantly better in modes 1 and 2, however, with 53-54% of the time in the comfort range versus 34% for mode 0. In all system, however, the average deviation from zone setpoint did not increase more than 0.5 °F in modes 1 and 2 versus mode 0, which is well within the normal variation of space temperatures in a building indicating that the occupants were highly unlikely to notice a difference between modes. Although individual system results were mixed, the variable volume modes did not perform significantly worse overall than the constant volume system and comfort performance was considered acceptable.

System Maintenance: System maintenance was acceptable as neither demonstration site reported any maintenance concerns with the retrofitted systems.

Overall, the demonstration of the conversion of a constant volume multizone to variable volume was successful as the results demonstrate the potential for the conversion to meet energy savings, comfort, cost and maintenance requirements. Based on a questionnaire distributed to many CONUS installations, the 2009 Base Structure Report and a poll of three large Army Installations, the potential savings from implementing this technique for all multizone systems in the DoD is estimated at over 400,000 million BTU a year (over $15 million per year). This is based on a range estimated from the questionnaire results of between 3,900 and 5,000 multizone air handlers in use across DoD. Selection of systems for application of this technique should consider multizone type and size, with preference given to larger multizones, and traditional 2-deck multizone systems.

1.0 INTRODUCTION

This project demonstrated a low cost technique to convert a constant volume multizone system to a more energy efficient variable volume multizone system. The primary motivation for the project was to measure the performance and document the technology to help promote its use. This included defining the applicability, project specifications, and implementation requirements leading to design guidance.

1.1 BACKGROUND

The current design practice for new HVAC systems that serve multiple zones is to use variable air volume technology. Still, the Army (and DoD) has a large existing inventory of energy inefficient constant volume multizone systems, an older technology also used to serve multiple zones. A constant volume multizone system can be converted to function as a variable air volume multizone system. Although there are various ways to perform this conversion, this project focused on an inexpensive technique that can be bundled with a direct digital controls (DDC) retrofit and is known to be minimally disruptive to building occupants.

When this project was conceived, using the number of installations, buildings, and square footage information from the 2009 Base Structure Report (BSR), the estimated savings of this technique if implemented at all CONUS Army, Air Force, Navy, and Marine Corps installations was 817,984 million BTU a year, which is worth over $29 million. Since there is no firm data on how many MZ systems exist in the DoD, this estimate was based largely an early informal poll of three large Army installations (Fort Bragg, Fort Hood and Fort Sill), which indicated that each had over 100 multizone systems, and on the general experience of the project team.

To help identify the applicability and interest in constant to variable volume multizone retrofits in the DoD a questionnaire was sent to many CONUS installations. After accounting for duplicated responses, there were responses from 78 different installations indicating a total of between 3,916 and 4,966 individual multizone air handlers in the existing DoD inventory at these installations. Forty-three of these

installations indicated an interest in implementing this technique, with 25 saying they were "very interested".

The large DoD inventory of multizone systems represents a significant potential for energy savings by converting these systems to variable air volume. This will also reduce greenhouse gas production, although the extent depends on the fuels used to generate electricity and heating and has therefore not been estimated.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the demonstration was to validate the effectiveness of a constant volume multizone to variable volume multizone retrofit approach in reducing energy consumption, analyze the economics of the upgrade, and provide technical guidance to help installations perform successful retrofits. The specific approach focusesd almost entirely on instrumentation and controls rather than the demolition and installation of ductwork and installation of variable air volume box terminal units.

The demonstration was performed on five multizone air handlers; three neutral deck multizone air handlers at Fort Bragg, NC and two traditional MZ air handlers at CERL in Champaign, IL.

The method consisted of upgrading pre-existing system(s) at low cost using commercially available technology and devices. The demonstration showed that this technology is viable and provides a well-defined and documented approach that is readily implemented.

1.3 REGULATORY DRIVERS

There are numerous drivers for saving energy and reducing greenhouse gases:

- Energy Policy Act of 2005, effective as of 8 August 2005
- 2005 Army Energy Strategy for Installations
- Executive Order 13423[2], signed on 24 January 2007 (see also Executive Order 13514)
- Executive Order 13514[3], Federal Leadership in Environmental, Energy, and Economic Performance; October 2009 (expands on Executive Order 13423)
- Executive Order 13693, Planning for Federal Sustainability in the Next Decade, 19 March 2015
- 2006/2007 Defense Science Board Key Facility Energy Strategy Recommendations
- Energy Independence & Security Act, effective 19 December 2007

Many of these policies, directives, and executive orders overlap in their requirements. Collectively the pertinent requirements are:

- Reduce energy by 20% by FY2015 (relative to 2003)
- Improve energy efficiency in buildings by 30% better than ASHRAE standards
- Reduce dependence on fossil fuels and make renewable energy at least 7.5% of total energy purchase by 2013 (DoD Internal Guidance calls for 25% by 2025)
- Improve energy security
- Construct or renovate buildings in accordance with sustainability strategies, including resource conservation, use, site criteria, and indoor environmental quality.
- Set greenhouse gas (GHG) emission reduction goals for FY2020 based on a FY2008 baseline

[2] Executive Order 13423 has been revoked with the publication of Executive Order 13693
[3] Executive Order 13514 has been revoked with the publication of Executive Order 13693

2.0 TECHNOLOGY DESCRIPTION

This technology converts a constant volume multizone system into a variable volume multizone system by focusing almost entirely on instrumentation and controls rather than the demolition and installation of ductwork and terminal units.

2.1 TECHNOLOGY OVERVIEW

Converting a constant volume multizone system to a variable air volume system ordinarily requires re-ducting and re-zoning to accommodate "VAV box" terminal units and is a major renovation effort that can be very costly, time consuming, and disruptive to the building occupants. This complete overhaul renovation approach is seldom considered attractive; therefore, multizone systems are usually operated as constant volume systems until they fail or otherwise warrant replacement (due to a building renovation for example).

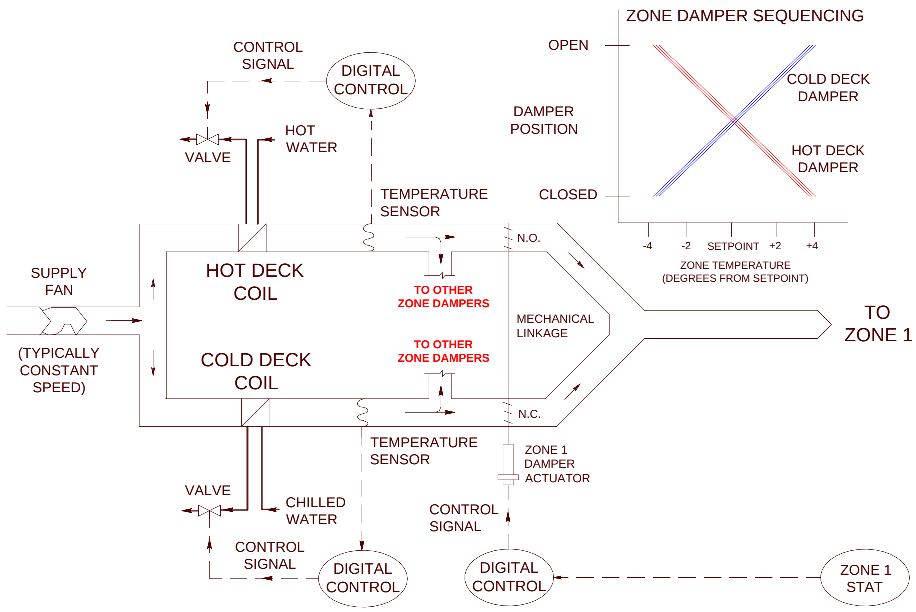
2.1.1 Multizone Unit Types

There are three typical configurations of multizone air handlers – standard, bypass, and neutral deck:

1. Standard Multizone: In a standard multizone system (Figure 1) the air handling unit contains a hot deck and a cold deck with associated heating and cooling coils. The system fan operates at a constant speed, and zone dampers blend the hot and cold air from these decks to create a zone air supply temperature to meet the demands of the zone. In most cases these zone dampers share a common shaft, and while separating these dampers might provide additional control options it is a difficult and costly task and generally considered not economical (and thus separation of the dampers is not considered a primary part of the retrofit technique).

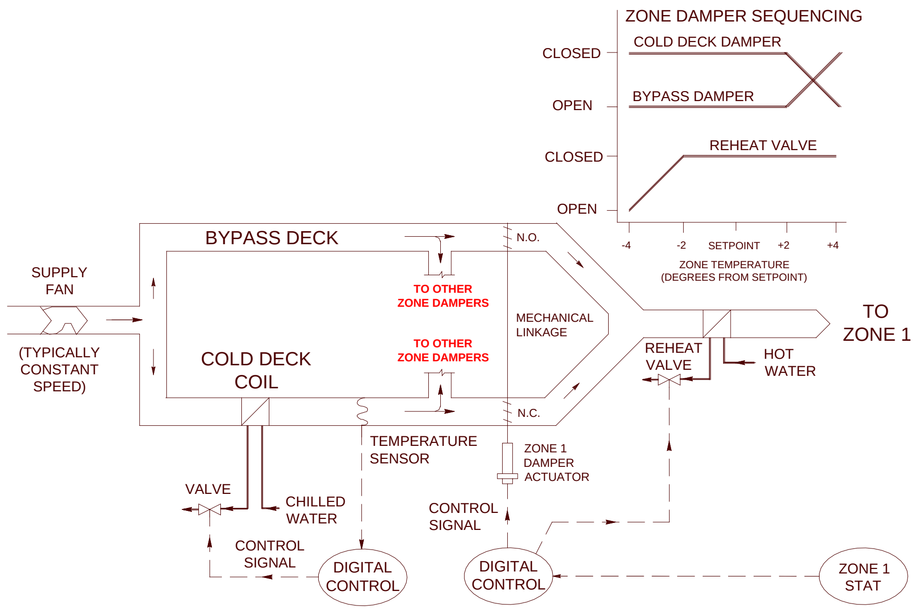
In an effort to save energy some Army installations operate the system seasonally to provide only hot or cold air by turning off the hot or cold decks. While this approach saves energy, operation of the system in heating-only mode can cause environmental issues within the building – most notably humidity control problems and the associated risk of mold development. An informal survey of Army installations indicates it is typical for both decks to be operated simultaneously.

Figure 1. Standard Multizone



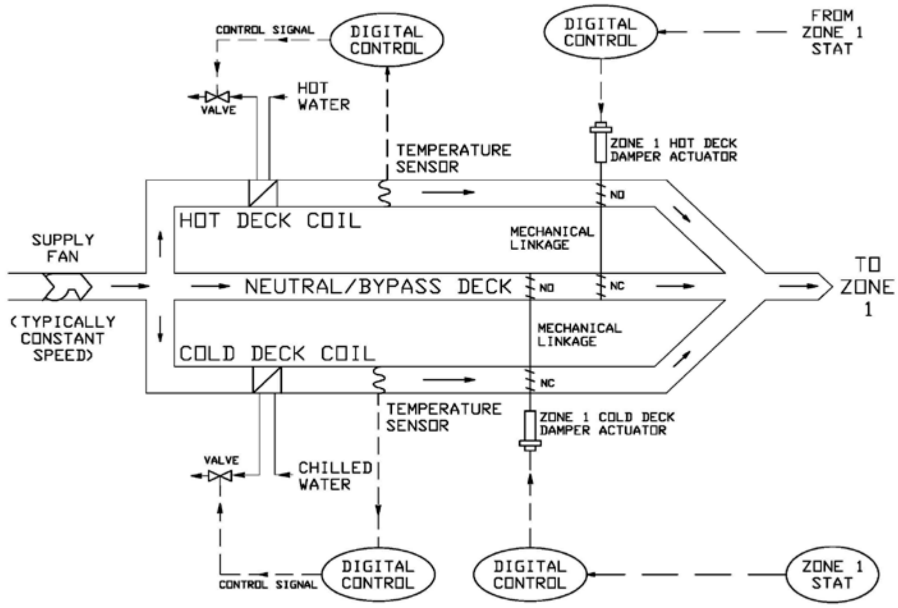
2. Bypass MZ: A bypass multizone unit (Figure 2) has a cold deck like a standard multizone unit, but in place of the hot deck it has a "bypass" deck. This "bypass" deck has no coil, and provides a path for unconditioned mixed air (return air and outside air) to flow to the zone dampers. The zone ducts themselves – downstream of the zone dampers – each have a small heating coil to provide for zone heating requirements. As with the standard multizone, the fan operates at a constant speed and the zone dampers are used to mix the cold deck and neutral deck airflows. The zone dampers and heating coils are staged such that the heating coils do not activate unless the "free heating" available from the neutral deck is insufficient to meet the needs of the zone (i.e. until the zone damper is open fully to the neutral deck). These systems are more energy efficient than standard multizones, since they can provide zone-by-zone heating (rather than a system-level heating coil) and can take advantage of the "neutral air" to provide "free heating".

Figure 2. Bypass Multizone



3. Neutral Deck MZ: A neutral deck multizone unit (Figure 3) has a cold deck and hot deck like a standard multizone unit but it also has a "neutral" deck. This "neutral" deck has no coil and provides a path for unconditioned mixed air (return air and outside air) to flow to the zone dampers. The zone control dampers are operated to prevent simultaneous heating and cooling. As with the standard multizone unit, the fan operates at a constant speed and the zone dampers are used to mix the cold deck or hot deck, and neutral deck airflows. These systems are more energy efficient than standard multizone units since they can provide zone-by-zone heating (rather than a system-level heating coil) and can take advantage of the "neutral air" to provide "free heating".

Figure 3. Neutral Deck Multizone



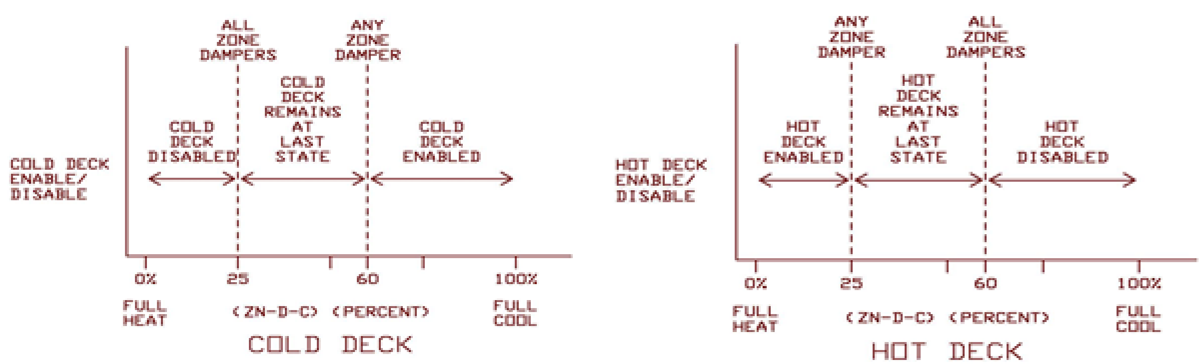
2.1.2 Control Logic Overview

The control logic (also referred to as 'sequence of control' or 'control strategy') consists of:

1) Adjust fan capacity based on the position of the zone dampers where fan speed is decreased until one of the zone dampers is at or near fully open to either heating or cooling. Reduced fan capacity reduces fan energy and also minimizes simultaneous heating and cooling inherent to conventional MZ systems.
2) Shut-off the hot (or cold) deck valve completely when there is no call for heating (or cooling), respectively, based on the commanded position of all zone dampers as illustrated in Figure 4.

As-built sequences of control are in APPENDIX F.

Figure 4. Hot/Cold Deck Valve Shutoff



2.1.3 Retrofit Overview

Starting with an air handler without modern DDC controls, the complete retrofit to DDC controls implementing variable volume control requires:

1) Variable frequency drive (VFD) installation: For fan capacity control where, as with any variable volume system, the ability to operate the fan at reduced speed provides energy savings.
2) Consideration of fan motor replacement: Fan motor replacement may provide for additional energy savings and compatibility with the VFD. The general recommendation for the VFD and motor is to specify a premium-efficiency motor that meets National Electrical Manufacturers Association (NEMA) requirements and a drive from the same supplier. In general, the VFD HVAC motor does not require a top-of-the-line "inverter-duty" motor which is very expensive, typically 3 to 4 times the cost of a premium efficiency motor. Premium-efficiency motors often carry the designation "inverter-ready" or "inverter-friendly," and may meet the NEMA requirements for HVAC applications.
3) Outside air flow measurement station installation: The existing constant volume system likely does not have a flow station, but using the variable volume conversion requires control of outside air flow to maintain ventilation and/or makeup air. (Note that there are some techniques that can be applied in cased where it’s physically impractical to install a flow measurement station, but only as a “fallback” so we don’t cover it here)
4) Upgrade of control system via programming changes and/or controller replacement for variable volume operation as well as to include demand controlled ventilation, an air side (dry bulb) economizer, and scheduled start/stop
5) Installation of new zone and air handling unit actuators and sensors as needed to support the conversion. It is generally advisable to replace pneumatic actuators with electric.

If the air handler already has modern DDC, or a retrofit to modern DDC is planned or underway, conversion to variable volume control requires items 1-3 from the above list.

In either case, except at the location where instrumentation or equipment might be installed, ductwork is not altered.

2.2 TECHNOLOGY DEVELOPMENT

CERL developed a very similar control strategy for a multizone system as part of a separate project in FY09 (ESTCP project EW-200938) where the control strategy appeared beneficial but was not fully developed nor evaluated. The control strategy and sequences of operation were developed and refined during this demonstration project in coordination with the designer of record.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The technique avoids or minimizes the inefficiency of simultaneous heating and cooling inherent to conventional multizone systems. Further energy savings are possible through outdoor ventilation air flow control and demand controlled ventilation.

2.3.1 Cost Advantages

The technique focuses almost entirely on instrumentation and controls rather than the demolition and installation of ductwork and terminal units, and is thus accomplished for a lower first cost, with less system down time and less disturbance to building occupants. In fact, no ductwork should be affected except at the location where instrumentation or equipment might be installed. The approach includes upgrading the system controls via programming changes or controller replacement and the installation of new and replacement actuators and sensors needed to support the conversion and to provide for monitoring and control of the system.

This technique is intended to avoid the more costly approach of converting a multizone system to a variable air volume (VAV) system through the renovation of ductwork and the installation of VAV box terminal units.

2.3.2 Performance Limitations

The age and condition of the typical multizone system presents the potential for unexpected maintenance or performance problems. Note that the demonstration will be conducted on multiple air handlers to ensure that results can be obtained even in the event of a failure of one or two units.

A MZ system contains multiple zone dampers. The control scheme depends on the position of each damper serving its respective zone/rooms. If no damper is fully open, the fan speed is reduced. Statistically, the greater the number of zone dampers, the greater the odds that one or more dampers will be fully open, lessening the opportunity for energy savings.

2.3.3 Cost Limitations

The control sequence for a variable volume system is more complex than for a constant volume, so there may be some additional costs associated with training and maintenance of the system. For the demonstration systems, these additional costs were negligible as the maintenance staff is accustomed to dealing with other similar complex control sequences.

2.3.4 Social Acceptance

This technology is expected to be well received. The only potential barrier to acceptance by operators, maintainers, or management is that in cases where digital controls are installed to replace non-digital controls, the system will be a bit more complicated and require training and familiarity with tools that maintenance staff may not be familiar with.

Multizone systems are generally considered easier to maintain than typical variable air volume systems due to the fact that all moving parts (dampers, valves, actuators) for a multizone system are located in the mechanical room (at the air handler) rather than throughout the facility in the plenum/ceiling area as is the case with VAV boxes.

3.0 PERFORMANCE OBJECTIVES

Constant volume multizone systems are outdated, but are very common within DoD facilities. The overall goal was to demonstrate an inexpensive conversion to a variable volume multizone system that reduces energy consumption without compromising occupant comfort. Reduced energy usage for this technology results in reduced need for fossil fuels (used to power/supply the HVAC systems) and a corresponding reduction in greenhouse gas emissions.

The performance objectives described in Section 3.1 and summarized in Table 1 define metrics and data to quantify reduced energy usage and thus the return on investment for this technology.

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

Performance data was collected for approximately one year where the systems were operated alternately in 2 modes: in the "pre-retrofit" mode it operate as a CAV system using only the pre-existing energy savings approaches, and in the "post retrofit" mode as a VAV system using all applicable energy savings approaches. The systems automatically switch between the modes on a set daily rotation and data was collected to assess energy use as well as system performance. Installed cost data was obtained as part of calculating the return on investment. Table 1 summarizes the performance objectives.

Table 1. Project Performance Objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Energy Usage	Energy Savings	Heating energy Cooling energy Fan energy	More than 10% energy savings compared to constant volume	Objective met for all units
Life Cycle Cost	Simple Payback Period (years) Savings to Investment Ratio (SIR)	Energy savings Energy cost Investment cost Maintenance cost (est.)	10 year payback for full retrofit. 3 year payback when added to planned retrofit ("incremental retrofit")	Full retrofit objective not achieved Incremental retrofit objective achieved for one system
Alignment with ASHRAE Comfort Zone	Percent of time spaces are in the "Comfort Zone". Space temperature deviation from thermostat setpoint.	Space/zone temperature Humidity Zone temperature setpoint	VAV system comfort the same or better than a constant volume system	Numerical objective met for some units.
Qualitative Performance Objectives				
Maintenance Implications	Acceptable, unacceptable or tenuous level of maintenance	Input from maintenance staff, Service Order info, operational status of HVAC system	Acceptable level of maintenance	Objective met for all units.

3.2 PERFORMANCE OBJECTIVE DESCRIPTIONS

As shown in Table 1, there are three quantitative and one qualitative performance objective for this demonstration. These performance objectives are described in detail in the following sub-paragraphs.

3.2.1 Energy Usage (Quantitative)

Purpose: Validate that the variable volume multizone system uses significantly less energy than the constant volume multizone system it replaced.

Metric: Multizone HVAC systems use both thermal and electrical energy:

- Heating coil (BTU): If the unit includes heating
- Cooling coil (BTU)
- Fan motor(s) (kWh): Supply fan; Return fan if the system incorporates one.

<u>Data</u>: Performance data was collected for approximately one year where the systems were operated alternately in 3 modes. In the pre-retrofit mode (Mode 0) the systems operated as constant volume multizone systems using only the pre-existing energy savings approaches / control strategy. There were 2 post-retrofit modes (Mode 1 and Mode 2) where, in both, the unit operated as a variable volume multizone system. In the first post-retrofit mode (Mode 1) the units were operated to maintain the outside air at a constant setting/quantity. In the second post-retrofit mode (Mode 2) the units were operated the same as in Mode 1 except a demand controlled ventilation (DVC) strategy was added all units except AHU-2 at Fort Bragg. The DCV strategy used either CO2 sensors (CERL AHU-1) or occupancy sensors (Fort Bragg AHU-1, Fort Bragg AHU-3 and CERL AHU-2). The systems automatically switched between the modes on a set daily rotation (at midnight) and data was collected every 15 minutes using the UMCS. Details of the test design are described in Section 5.

<u>Analytical Methodology</u>: Statistical analysis of the collected data is described in Section 6.

<u>Success Criteria</u>: The goal of this performance objective was for each of the retrofitted systems to save more than 10% energy compared to the pre-retrofit constant volume systems.

<u>Results</u>: Success. The retrofitted systems had energy reductions significantly greater than 10%, ranging from 24%-60% energy reduction. Energy savings are described in detail in Section 6.

3.2.2 Life Cycle Cost (Quantitative)

<u>Purpose</u>: The payback value of any energy efficiency technology dictates its potential for adoption.

<u>Metric</u>: Simple Payback Period (years), Savings to Investment Ratio (SIR)

<u>Data</u>: Capital investment data was estimated using RSMeans data, and energy usage (meter) data was logged by the UMCS. The cost analysis is described in Section 7.

<u>Analytical Methodology:</u> Computations were performed using the NIST Building Life Cycle Cost version 5 (BLCC5) program as described in Section 7.

<u>Success Criteria</u>: A payback period of less than 10 years for a full retrofit and a payback period of less than 3 years for the incremental retrofit.

<u>Results</u>: Partial success. Table 2 summarizes the payback periods for each system based on operation in Mode 2 for both a full and incremental retrofit. AHU-2 at CERL was the only system to meet both success criteria.

Table 2. Payback Period for Demonstration Systems (Mode 2)

	Full Retrofit	Incremental Retrofit
CERL AHU-1	n/a	7 years
CERL AHU-2	10 years	3 years
Fort Bragg AHU-1	n/a	10 years
Fort Bragg AHU-2	n/a	n/a
Fort Bragg AHU-3	n/a	13 years

Although the success criteria wasn't met for all systems, we demonstrated significant energy savings and the potential to meet the LCC goals for larger systems which use more energy. Also, when applied as the incremental retrofit most of the demonstration systems paid back within the 15-year life of the renovated system, indicating that there is very little reason NOT to apply this technique if already engaging in a DDC retrofit.

Considering the drastic variations in utility costs across the country the potential for this retrofit technique to be successful was analyzed using the highest and lowest average utility costs on a state-by-state basis. [5,6] The incremental retrofit payback period was examined for a representative 3 HP AHU derived from averaging the 4, 3 HP AHUs in the study, and for the single 8 HP AHU in the study. The results from this analysis can be seen in Table 33 and Table 34 and show that the representative 3 HP AHU varies between a 3 and 13 year simple payback and the 8 HP AHU varies between a 2 and 12 year simple payback depending on the best and worst case utility scenarios in the continental United States.

3.2.3 Alignment With ASHRAE Comfort Zone (Quantitative)

Purpose: Energy reduction/conservation technologies such as this run some risk of reducing occupant comfort therefore this was monitored and measured.

Metric: ASHRAE standard 55-2010 defines thermal environmental conditions for human occupancy. Occupant comfort was gaged by calculating the percent of time that the spaces were in the ASHRAE "Comfort Zone" using the ASHRAE 55 comfort calculation. In addition, for each space, temperature deviation from the space thermostat setpoint was computed. An occupant comfort questionnaire was considered, but was rejected due to concern about the subjective nature of a questionnaire and the amount of time/effort it would take to properly design and implement a questionnaire.

Data: Performance data was collected for approximately one year where the systems were operated alternately in 3 modes as described previously. Space temperature and relative humidity data pertinent to the ASHRAE 55 comfort zone calculation was collected from each zone every 15 minutes using the UMCS.

Analytical Methodology: The procedure included computing the ASHRAE comfort index value for each zone every 15 minutes. As a secondary measure of system performance the deviation of zone temperature from its thermostat setpoint was calculated and compared for each operational mode.

Success Criteria: Comfort for the renovated system the same or better than the constant volume system. This criteria was evaluated analyzed by comparing the percentage of time the system was within the ASHRAE 55 comfort zone across modes and the average zone temperature deviation from setpoint across modes.

Results: The two systems at CERL performed nearly the same across all three operating modes. The difference across modes was more significant at Fort Bragg, where 2 had worse comfort performance in the variable volume modes, where one system spent 29-33% of time within the thermal comfort range in modes 1 and 2 versus 39% of time the time for mode 0, and the other system spending 55% of the time in the comfort range in modes 1 and 2 versus 61% in mode 0. The third system at Fort Bragg performed significantly better in modes 1 and 2, however, with 53-54% of the time in the comfort range versus 34% for mode 0. In all system, however, the average deviation from zone setpoint did not increase more than 0.5 °F in modes 1 and 2 versus mode 0, which is well within the normal variation of space temperatures in a building indicating that the occupants were highly unlikely to notice a difference between modes. Although individual system results were mixed, the variable volume modes did not perform significantly worse overall than the constant volume system and comfort performance was considered acceptable.

Additional Commentary:
Upon further consideration, and with the benefit of hindsight, expecting the renovated system to perform as well or better based on this numeric analysis may have been unreasonable. The nature of the control strategy for the variable volume system should be expected to increase the spread of temperature ranges. This is due to several factors including:

- Lower flow systems tend to be slower to react to zone temperature changes, increasing the chance that zones will drift further from setpoint temporarily
- The fan speed control loop requires that a zone drift from setpoint a significant amount before increasing fan speed, widening the expected range of zone temperatures
- The variable volume system introduces inter-dependency between zones that don't exist in the constant volume system, as a single zone can cause the system air volume to increase, which the other zones must react to. Since the zones are controller off zone temperature, and not zone flow, this means that the temperature of the other zones will need to drift from setpoint before the zone dampers will react.

Some of these factors could possibly be addressed by additional tuning of the control loops for the zones and the supply fan, but this is uncertain. The tuning selected for the demonstration was intentionally conservative (not fast acting) in order to avoid wild perturbations of control, and this remains the recommended approach.
Given the challenges of maintaining "tight" control with the variable volume control strategy, the comfort analysis is reassuring. Although the demonstration systems did not meet the numerical goal of being "as good or better", they maintained very nearly the same comfort level while providing significant energy savings.

3.2.4 Maintenance Implications (Qualitative)

Maintenance Implications performance objective measures the level of maintenance the renovated system requires as compared to the original system. This technology calls for upgrading the system to include a variable frequency drive (VFD) on the air handling unit fan motor(s), addition of an outside air flow measurement station and possible replacement of digital controllers and zone damper actuators. As part of the upgrade and during the course of the demonstration other devices may also be replaced or repaired on these existing (and aging) systems. These changes can affect the maintenance for better or worse and therefore should be monitored/recorded. This metric is Qualitative since it is difficult to quantify impacts on maintenance. The overall DPW impression of the maintenance required by the system is the most useful/practical measure of the maintenance burden.

Purpose: The system must not be a maintenance burden. However, quantifying maintenance can be difficult, plus the renovated system(s) will be more visible and more scrutinized (in part because it will have a user interface and performance data logging) than the system it replaces; therefore, a fair comparison to the old/original system is not likely possible. With the user interface and our data logging, maintenance and performance problems are more likely to be caught/observed. The overall purpose of this metric is to ensure that the garrison DPW does not view the renovated system as an additional maintenance burden, as doing so may cause them to resist the implementation of this method to other systems.

Metric: The metric is acceptable, unacceptable or tenuous level of maintenance, as determined qualitatively through input from the maintenance staff

Data: DPW maintenance staff at CERL welcomed the technology upgrade. Particularly in the case where the pneumatic controls were replaced on AHU-2, this was considered a significantly beneficial improvement/upgrade primarily because the controls were interfaced to the UMCS and the system performance could be monitored and recorded. In addition, alarms provided notification of problems – mainly if the air handler was not running when it should be. The unit shut down due to activation of the freeze stat several times during the demonstration. This was attributed to the new ventilation controls but still did not deter maintenance staff appreciation of the upgrade.

Success Criteria: The technology has an acceptable level of maintenance.

Results: Success. Neither demonstration site reported any maintenance concerns so maintenance is considered acceptable. In addition, the integration AHU-2 at CERL was reported to have improved maintainability of the system.

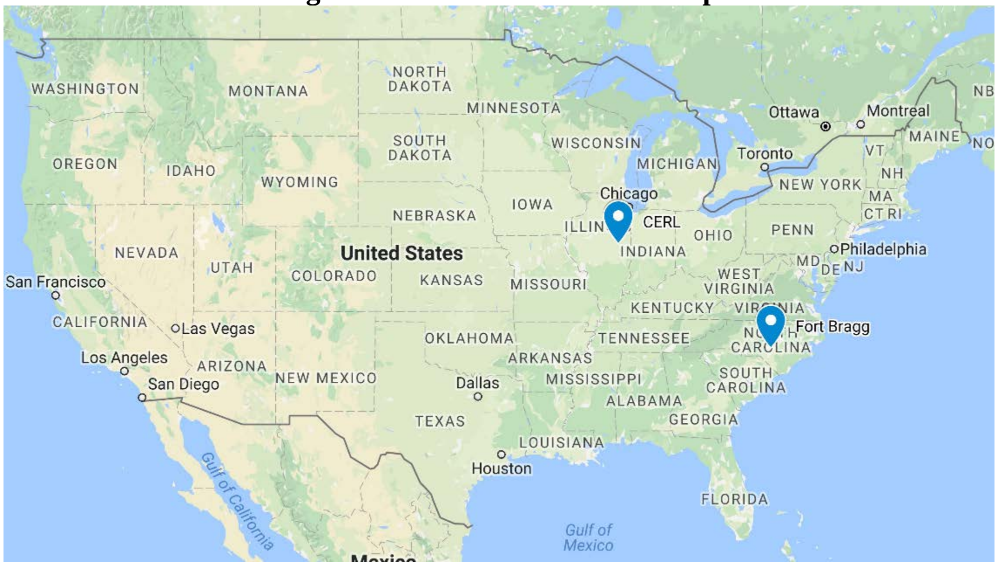
4.0 FACILITY/SITE DESCRIPTION

The demonstration was performed at Fort Bragg NC and ERDC-CERL Champaign IL. Three air handlers at Fort Bragg were selected, and two at CERL, based on detailed survey criteria and discussions with the local operation and maintenance (O&M) staff and other appropriate DPW staff at each site. Many factors helped determine the best candidate; some of the more important criteria included preference for systems that:

- Are already remotely monitored via building automation system?
- Are larger units that operate a lot of hours and provide more potential for savings?
- Are units in reasonably good working order?
- Have hydronic systems that allow BTU meter installation?

Detailed surveys were performed. Included in these surveys were mechanical system sketches, measured diffuser airflows and otherwise determined system capacities, and photographs of all system components, equipment, and hardware.

Figure 5. Demonstration Sites Map



4.1 FORT BRAGG

Demonstration Site Description: Fort Bragg is a Forces Command installation located in Cumberland and Hoke Counties, North Carolina. Due to its age it has numerous existing HVAC systems including multizone systems. Fort Bragg consists of approximately 161,000 acres. Fort Bragg's facilities include 2,176 structures (with approximately 1200 considered 'major') and 25.2 million total sq. ft. of buildings.

Key Operations: May of Fort Bragg's permanent facilities/buildings contain multizone HVAC systems.

Command Support: A MOU between Fort Bragg and ERDC-CERL is in place. Department of Public Works director, Mr. Gregory Bean, fully supports the demonstration at their site. We met with him during a site visit and have worked with him and Fort Bragg personnel on several other occasions over the years. We've met with Mr. Russ Hayes, the lead Mechanical Engineer in the DPW Business Operations and Integration Division, Mr. Coby Jones the Energy Program Coordinator and UMCS manager, Mr. Rudy Muccitelli Engineering Technician, and Ashley Gore, DPW O&M shop Work Leader.

Communications: This site has an existing UMCS which will be used for data collection on site. This eliminates the difficulties, such as Information Assurance/DIACAP issues, associated with establishing a new monitoring system. Data will be collected by DPW and put on CDs which will be periodically mailed to CERL.

Figure 6. Example Air Handling Unit, Zone Ducts and Zone Actuators (at Fort Bragg)

4.2 CERL

Demonstration Site Description:. CERL is located in Champaign Illinois. It consists of three buildings interconnected by two hallways. The location of the two AHUs to be used for demonstration are in building 2, mechanical room 2127 and above Room 2014.

Key Operations: This research laboratory consists of laboratories, offices, and conference rooms.

Command Support: The Lab Director, Energy Branch chief, and DPW all fully support this effort.

Communications: A dedicated UMCS network was in place and used.

Figure 7. Example Zone Dampers, Zone Actuators and VFD Drives (at CERL)

4.3 DEMONSTRATION SYSTEM SUMMARY

Table 3 summarizes basic characteristics of the systems included in the demonstration project.

Table 3. Demonstration System Summary

Site	System	Floor area (sf)	Size (cfm)	No. of Zones	Comment
Fort Bragg Bldg A-1985	AHU 1	2,983	4,620	3	~10 years old. Neutral deck MZ
	AHU 2	4,328	4,870	9	
	AHU 3	4,837	4,870	8	
ERDC-CERL Bldg 2	AHU 1	8,800	8,550	5	~40 years old. Traditional MZ. Mainly offices. DDC upgrade w/in past 3 years.
	AHU 2	2,400	3,475	3	~40 years old. Traditional MZ. Mostly conference rooms.

5.0 TEST DESIGN

A conventional multizone system performs simultaneous heating and cooling and delivers a constant volume of airflow in order to meet the demands of the zones. This is much less efficient than a variable volume system that varies the airflow in order to meet zone demand.

Questions addressed by this demonstration included:

1. To what extent can a VAV MZ system save fan, heating, and cooling energy?
2. What is the life cycle cost of the technology?
3. Is maintenance of the technology considered by the maintenance staff to be an issue or problem?
4. To what extent is occupant comfort affected?

5.1 CONCEPTUAL TEST DESIGN

Independent variable: The independent variable is the type of air flow system, either constant volume or variable volume.

Dependent variable(s): The dependent variable is the amount of energy used by the building for HVAC. This includes air handling unit fan electricity usage (kWh), cooling coil capacity (BTUs),

heating coil capacity (BTUs). (Also see para 5.2 ‘Baseline Characterization’ Reference Conditions below).

<u>Controlled variable(s)</u>: The controlled variables include the heating and cooling loads such as occupancy, equipment, weather (outside air temperature, humidity, and wind speed), and sun radiation. We will mathematically control these through normalization or averaging: We will compare the dependent variables while changing the independent variable by rotating between operating modes daily, with a switchover at midnight, for a period of 1 year. The nightly rotation will ensure that each mode sees operation on each day of the week, and will distribute multi-day duration weather extremes across the different modes.

In the constant volume pre-retrofit mode (Mode 0) the unit operates using only the pre-existing energy savings features and controls, and in the “post retrofit” mode it operates as a VAV system using all applicable energy savings features and controls.

In order to validate the energy savings from demand controlled ventilation there were two “post retrofit” configurations (modes) for variable volume operation. In Mode 1, the quantity of ventilation air (outdoor air) is fixed at a specific flow rate, while in Mode 2 this quantity is varied based on zone occupancy as determined by occupancy sensors or CO_2 sensors.

<u>Hypothesis</u>: A constant volume multizone system converted to a variable volume multizone system will use less energy, have an acceptable or reasonable life cycle cost, yield the same or better occupant comfort, and not be viewed as a maintenance burden.

<u>Test Design</u>: Constant volume multizone systems were converted to variable volume multizone systems. The UMCS was used to collect energy use data on systems in both configurations.

<u>Test Phases</u>:

- Select AHUs to include in the demonstration
- Design/specify each AHU retrofit including monitoring instrumentation
- Perform Quality Verification and Commissioning
- Collect Data in both constant volume and variable volume configurations
- Analyze data
- Report results

Table 4. Control Loop Options by Test Mode for CERL AHUs

AHU/TEST MODE	FAN CAPACITY CONTROL		OUTSIDE AIR FLOW CONTROL			MIXED AIR TEMP CONTROL WITH ECONOMIZER	HOT DECK TEMP CONTROL				COLD DECK TEMPERATURE CONTROL - COLD DECK VALVE CONTROL ON/OFF		ZONE TEMP CONTROL	REHEAT COIL CONTROL	PREHEAT COIL CONTROL
							DETERMINITATION OF HD-T-SP		HD VALVE CONTROL ON/OFF						
	CONSTANT FAN SPEED	VARIABLE FAN SPEED	FIXED DAMPER POSITION	CONTROL TO FIXED FLOW SETPOINT	DEMAND CONTROL VENTILATION	MIXED AIR TEMPERATURE CONTROL WITH ECONOMIZER	FIXED HD SETPOINT (NO RESET)	HD SETPOINT RESET BASED ON OA-T	HOT DECK VALVE CONTROL ALWAYS ON	HOT DECK VALVE CONTROL ON/OFF BASED ON ZONE DAMPER COMMAND	COLD DECK VALVE CONTROL ALWAYS ON	COLD DECK VALVE CONTROL ON/OFF BASED ON ZONE DAMPER COMMAND	ZONE TEMPERATURE CONTROL	REHEAT COIL CONTROL (AHU-2-001 ONLY)	PREHEAT COIL CONTROL (AHU-2-002 ONLY)
CERL AHU-2-001															
Basic Mode	X		X			X		X	X		X		X	X	
Advanced Mode #1		X		X		X	X			X		X	X	X	
Advanced Mode #2		X			X	X	X			X		X	X	X	
CERL AHU-2-002															
Basic Mode	X		X			X		X	X		X		X		X
Advanced Mode #1		X		X		X	X			X		X	X		X
Advanced Mode #2		X			X	X	X			X		X	X		X

Table 5. Control Loop Options by Test Mode for Fort Bragg AHUs

AHU/TEST MODE	FAN CAPACITY CONTROL		OUTSIDE AIR FLOW CONTROL			MIXED AIR TEMP CONTROL WITH ECONOMIZER	HOT DECK TEMP CONTROL				COLD DECK TEMPERATURE CONTROL - COLD DECK VALVE CONTROL ON/OFF		ZONE TEMP CONTROL
							DETERMINATION OF HD-T-SP		HD VALVE CONTROL ON/OFF				
	CONSTANT FAN SPEED	VARIABLE FAN SPEED	FIXED DAMPER POSITION	CONTROL TO FIXED FLOW SETPOINT	DEMAND CONTROL VENTILATION	MIXED AIR TEMPERATURE CONTROL WITH ECONOMIZER	FIXED HD SETPOINT (NO RESET)	HD SETPOINT RESET BASED ON OA-T	HOT DECK VALVE CONTROL ALWAYS ON	HOT DECK VALVE CONTROL ON/OFF BASED ON ZONE DAMPER COMMAND	COLD DECK VALVE CONTROL ALWAYS ON	COLD DECK VALVE CONTROL ON/OFF BASED ON ZONE DAMPER COMMAND	ZONE TEMPERATURE CONTROL
FORT BRAGG A-1895 AHU-1													
Basic Mode	X		X			X		X	X		X		X
Advanced Mode #1		X		X		X	X			X		X	X
Advanced Mode #2		X			X	X	X			X		X	X
FORT BRAGG A-1895 AHU-2													
Basic Mode	X		X			X		X	X		X		X
Advanced Mode #1		X		X		X	X			X		X	X
Advanced Mode #2		X		X		X	X			X		X	X
FORT BRAGG A-1895 AHU-3													
Basic Mode	X		X			X		X	X		X		X
Advanced Mode #1		X		X		X	X			X		X	X
Advanced Mode #2		X			X	X	X			X		X	X

5.2 BASELINE CHARACTERIZATION

Reference Conditions: A total of five different AHUs are included in the demonstration project. Below is a comprehensive list of the data points collected that were common to the units tested, and others were available depending on the configuration of the specific AHU/system:

- AHU fan electricity usage (watts)
- Cooling coil energy (BTUs)
- Heating coil energy (BTUs)
- Temperature in each zone (°F)

- Relative humidity in each zone, (percent)
- Zone thermostat temperature setpoint (°F)
- Zone damper command/position (% open)
- Zone/space carbon dioxide (CO_2) levels (CERL AHU-1 only)
- Outside air temperature (°F)
- Outside relative humidity (%RH)
- AHU outside airflow (cfm)

Baseline Collection Period: There is no baseline period, per se. The baseline is the constant volume (Mode 0) mode of operation. The systems were configured to automatically switch between this constant volume mode and the variable volume modes daily for one year. The data collected when the system was operating in the constant volume mode was used to define the baseline for comparison to the variable volume modes.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The conversion of a constant volume multizone air handler to a variable volume multizone air handler focuses on commercially available equipment, instrumentation, and controls - most notably the installation of a variable speed fan. The conversion also includes upgrading the controls via programming changes or controller replacement and the installation of new or replacement actuators and sensors – including the addition of outdoor airflow measurement - needed to support the conversion.

Key components of the system include the Variable Frequency Drive (VFD), premium efficiency (not inverter duty/grade) motor suitable for use with a VFD, outside airflow measurement sensor/station, zone dampers and electric actuators, sensors, actuators, and the sequence of operation.

It may employ new digital controller(s) (or possibly the modification of the existing digital controls). Where applicable, systems may be enhanced by incorporating a demand controlled ventilation scheme (which is fairly typical in a modern retrofit) including CO2 sensors in one or more zones/spaces.

The retrofit, in some cases, can replace older controls with microprocessor based direct digital controls providing improved accuracy and reliability. Digital controls also supports the application of other energy savings techniques such as automatic adjustment of the hot and/or cold deck discharge air temperature setpoints, after-hours (unoccupied mode) zone temperature setback and/or system shutdown, outdoor ventilation air flow control and demand controlled ventilation that might not have been in place with the existing/older system.

5.3.1 Data Collection Equipment

All sensors and meters used to collect data were integrated into the UMCS which was used to log the needed data. This instrumentation includes:

- Watt-hour meter. Used to collect fan motor energy and electric chiller energy.
- BTU meter. Used to measure water coil energy. Each BTU meter measures water flow (gpm) along with water temperature at the coil inlet and outlet)
- Temperature in each zone (°F). Will use temperature sensor built in the wall-mount module sometimes referred to as a thermostat.
- Relative humidity in each zone, (%RH). Will use a wall mount sensor.
- Zone thermostat temperature setpoint (°F)
- Zone damper command/position (% open). We used the signal from the digital controller where the digital controller generated a control signal to move/position the damper.

- Outside air temperature (°F)
- Outside relative humidity (%RH)
- Airflow in duct (cfm). We used duct-insertion type multi-point flow sensor, the hotwire anemometer type, not pitot tube, since the hotwire type is more accurate at low airflow rates.

5.4 OPERATIONAL TESTING

Five systems were renovated. Commissioning (Cx) included quality verification testing of the system to ensure that they switched between the basic operational modes. Cx also included stepping through the sequence of operation for each mode to ensure that the controls functioned properly. A commissioning agent helped ensure that the renovation was properly accomplished.

No modeling or simulation was performed although some estimation was performed to account for a minimal amount of lost or bad data.

Retrofits occurred between May and August 2015. Data collection began September 2015 and was completed September 2016.

5.5 DUCT LEAKAGE TESTING

Since the demonstration systems are existing systems, duct leakage testing was conducted on four of the five demonstration systems to verify that duct leakage levels were acceptable.

There are two methods of duct pressure testing:

1) Duct pressurization: The duct ends and diffusers are sealed, and the duct is pressurized using a separate fan, measuring pressure to determine leakage. This method in accordance with the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) duct leakage testing method, but is costly due to the labor involved. This method was used on one air handler at CERL.
2) Differential CFM: Measure air flow at the Air Handler and at each diffuser and compare air supplied to air delivered, where the difference is the duct leakage. This method is less accurate, but significantly less expensive, and was used for all four air handler measured.

Figure 8 shows the separate fan used for testing method 1 (left side of figure) and the airflow measurement of a diffuser when using method 2 (right side of figure).

Figure 8. Duct Leakage Testing

The duct leakage test results are summarized in Table 6. These results are within the expected range for systems of this age and type, and no additional duct sealing was performed as part of this demonstration.

Table 6. Duct Leakage Results

System	Measured Airflow	Leakage % (Method 1)	Leakage % (Method 2)
CERL AHU-2	2869 cfm	19%	18%
Fort Bragg AHU-1	3750 cfm	--	16%
Fort Bragg AHU-2	5184 cfm	--	11%
Fort Bragg AHU-3	6503 cfm	--	3%

5.6 SAMPLING PROTOCOL

Data Description: Data collected is listed/described in section 5.3 "Reference Conditions". Each data point was collected at 15 minute intervals for 1 year. There were no less than 40 data points per MZ system. The data was collected using the local UMCS.

5.7 SAMPLING RESULTS

The data collected for each system is described above. Table 7 shows an example of a trend log. Complete trend data is available through the Points of Contact listed in Appendix A.

Table 7. Example Trend Log

Timestamp	AHU Mode	AHU-1 SF VFD speed (%)	AHU-1 OAF SP (cfm)	AHU-1 SF VFD power (kW)	AHU-1 RAT (deg F)	AHU-1 RA CO2 (ppm)	AHU-1 RF VFD speed (%)	AHU-1 RF VFD power (kW)
9/10/2015 12:45	2	100.0	1,877.3	3.6	72.8	573.0	94.7	0.9
9/10/2015 13:00	2	100.0	1,957.8	3.6	72.9	570.0	86.7	0.7
9/10/2015 13:15	2	100.0	1,957.8	3.6	74.5	608.0	0.0	0.0
9/10/2015 13:30	2	46.5	2,038.4	1.2	74.4	620.0	58.3	0.3
9/10/2015 13:45	2	71.6	2,277.8	1.2	73.3	621.0	61.8	0.3
9/10/2015 14:00	2	80.8	2,197.3	2.9	73.2	613.0	91.7	0.8
9/10/2015 14:15	2	68.7	2,358.3	1.3	74.0	620.0	61.8	0.3
9/10/2015 14:30	2	67.3	2,358.3	1.3	73.7	629.0	61.8	0.3
9/10/2015 14:45	2	67.3	2,197.3	1.3	73.7	631.0	61.8	0.3
9/10/2015 15:00	2	67.3	1,718.4	1.4	73.9	611.0	61.8	0.3
9/10/2015 15:15	2	82.5	1,957.8	3.8	73.4	611.0	94.7	0.9
9/10/2015 15:30	2	100.0	1,798.9	3.8	73.1	595.0	94.7	0.9
9/10/2015 15:45	2	66.8	1,637.9	0.6	73.5	590.0	45.0	0.1
9/10/2015 16:00	2	53.5	2,197.3	3.7	74.0	590.0	45.0	0.1
9/10/2015 16:15	2	55.0	2,197.3	0.2	74.4	590.0	25.0	0.0

6.0 PERFORMANCE ASSESSMENT

6.1 ENERGY PERFORMANCE

The Energy Performance Metric is for the renovated systems to use more than 10% less energy than pre-retrofit system.

6.1.1 Primary Metrics For Evaluating Energy Performance

In order to quantitatively determine whether the performance objective for more than 10% in total energy savings (as compared to constant volume operation) would be met, the following metrics were defined:

1. Fan energy usage: fan energy use as reported by the VFD. Where the air handler has two fans (supply and return) the energy use is reported as the total of both. Fan data was recorded as interval kW data and converted to kWh

2. Heating energy: energy used at the air handler via hot water valve to meet hot deck coil discharge set point and as measured through BTU meters measuring coil flow and temperature differential (recorded as interval Btuh data and converted to kBtu)
3. Cooling energy: energy used at the air handler via chilled water valve to meet cold deck coil discharge set point and as measured through BTU meters measuring coil flow and temperature differential (recorded as interval Btuh data and converted to kBtu)

Once energy usage data is collected by control mode (constant volume vs variable volume sequences) the data will be normalized by equipment runtimes and weather conditions. This normalized data will be used to determine if the 10% energy reduction target was met successfully.

6.1.2 Collection Of UMCS Trend Data In Baseline And Retrofit Modes

Existing Utility Monitoring and Control Systems (UMCSs) were leveraged as built-in historians for the above variables. Fifteen minute interval data was collected and exported as time-series spreadsheet data as shown in Table 8. Each system was rotated daily through the three operating modes, switching between modes daily at midnight:

1. Mode 0 (baseline operation): mimics preexisting sequences of operation that maintain constant fan speeds with air volumes near 100% design capacities
2. Mode 1 (VAV operation): use of VFDs to ramp down fan speeds to better match load as indicated by tracking critical (most open) damper positions
3. Mode 2 (VAV + DCV operation): Variable air volume operation with additional control logic to reduce minimum outside air volumes based on zone occupancy, using either zone CO2 sensors or zone occupancy sensors., referred to as demand controlled ventilation (DCV).

Table 8. Example Trend Data

Timestamp	AHU Mode	AHU-1 SF VFD speed (%)	AHU-1 OAF SP (cfm)	AHU-1 SF VFD power (kW)	AHU-1 RAT (deg F)	AHU-1 RA CO2 (ppm)	AHU-1 RF VFD speed (%)	AHU-1 RF VFD power (kW)
9/10/2015 12:45	2	100.0	1,877.3	3.6	72.8	573.0	94.7	0.9
9/10/2015 13:00	2	100.0	1,957.8	3.6	72.9	570.0	86.7	0.7
9/10/2015 13:15	2	100.0	1,957.8	3.6	74.5	608.0	0.0	0.0
9/10/2015 13:30	2	46.5	2,038.4	1.2	74.4	620.0	58.3	0.3
9/10/2015 13:45	2	71.6	2,277.8	1.2	73.3	621.0	61.8	0.3
9/10/2015 14:00	2	80.8	2,197.3	2.9	73.2	613.0	91.7	0.8
9/10/2015 14:15	2	68.7	2,358.3	1.3	74.0	620.0	61.8	0.3
9/10/2015 14:30	2	67.3	2,358.3	1.3	73.7	629.0	61.8	0.3
9/10/2015 14:45	2	67.3	2,197.3	1.3	73.7	631.0	61.8	0.3
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9/10/2015 15:45	2	66.8	1,637.9	0.6	73.5	590.0	45.0	0.1
9/10/2015 16:00	2	53.5	2,197.3	3.7	74.0	590.0	45.0	0.1
9/10/2015 16:15	2	55.0	2,197.3	0.2	74.4	590.0	25.0	0.0

Data was collected for a period of 12-13 months (12 months for Fort Bragg, 13 months at CERL), and a subset of these data were used in the evaluation of energy performance. The data used for the analysis was processed to remove data collected during non-operational periods and to ensure comparable data sets for each operating mode. The means by which the data was processed prior to analysis and the manner in which the analysis of the data was conducted is described in detail in the following sections.

6.1.3 Removing Data When Multizone Units Were Not Operating

The first step in conditioning data for analysis was filtering trend points from the final database of 15-minute interval readings to remove those data that lacked analytical value with regards to the performance of the system in each mode. Specifically, data meeting at least one of the following criteria were removed:

1. Outside the daily operating hours: all AHUs were scheduled on/off and not operated evenings or weekends during the study, therefore only daytime AHU data was used in the analysis (i.e. M-F 6:30am-5:15pm for CERL, M-F 5:30am-6:00pm for Fort Bragg).
2. Holiday exceptions: The AHUs were not operated on Federal holidays therefore only non-holiday AHU data was used in the analysis.
3. Random off times detected: when the building or AHU was scheduled for operation but contained small instances with zero fan wattage registered, these small instances were removed (this is most likely due to spot maintenance or ongoing servicing of related AHU equipment).

6.1.4 Selection Of Data Series Points To Eliminate Statistically Significant Variation

With datasets trimmed to represent runtime conditions only, the next step in the data analysis process included validation that no statistically significant variation in energy drivers existed outside the mode changes themselves. To facilitate this check, a statistical analysis of variability was performed between multizone modes for each of the sites. The three candidates considered as potential energy performance drivers to include in an analysis of variability are Interior Loads, Day of the Week, and Outside Air Conditions.

6.1.4.1 Interior Loads

Consideration was given to interior zone loads that may have been unevenly distributed across operation modes. Fluctuating interior zone loads could include sensible gains from irregularly used electronics or sensible and latent gains from intermittent occupant densities. The demonstration did not includea reliable metric to evaluate statistical differences in zone loads but based on known room usage patterns it is reasonable to assume that zone load profiles are evenly distributed across operation modes. Furthermore, air-side economizer control logic and minimum outside air requirements limit the effects of zone loads on energy usage at AHU heating and cooling coils. The daily rotation of operating modes and the operation of the system over long periods of time should adequately account for the variations in internal loads, so no further refinement of the data was performed to address this driver of energy use.

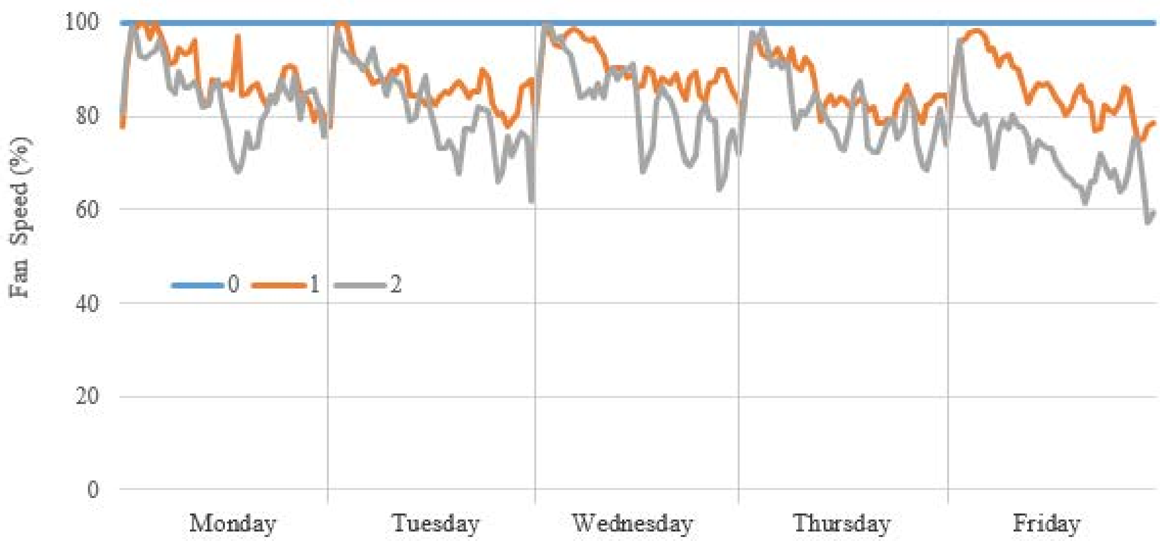
6.1.4.2 Day of the Week

It is possible that on certain days of the week or times of the day energy usage patterns could vary and uneven distribution of days across modes could skew results. Monday mornings, for instance, could have offered an additional pickup load when bringing rooms to zone temperature set point after a weekend of no multizone unit operation. Although the rotation through modes of operation will largely even out the days of the week between modes, the impact of the day of the week was examined to determine whether it was necessary to process the data to ensure the same distribution of days between modes.

To identify potential shifts in daily energy use, the supply fan speed was plotted by day and examined for significant discrepancies between the days of the week (Figure 9). With the possible exception of CERL AHU-1, where mode 2 operations (variable volume with demand-controlled ventilation) suggest that zones may be regularly less occupied on Fridays, there was no indication of the day of the week having a significant effect on energy use. As Friday data points represented 21% of the final CERL AHU-1 dataset for mode 2 compared to 23% for modes 0 and 1, there is potential for slight understating of energy savings expected from demand-controlled ventilation. Overall, however, effects from marginally unequal

distributions of hourly or daily data between modes are considered negligible and no statistical analysis or corrections were attempted.

Figure 9. CERL AHU-1 Average Weekly Supply Fan Speed Profile (During Operating Hours)

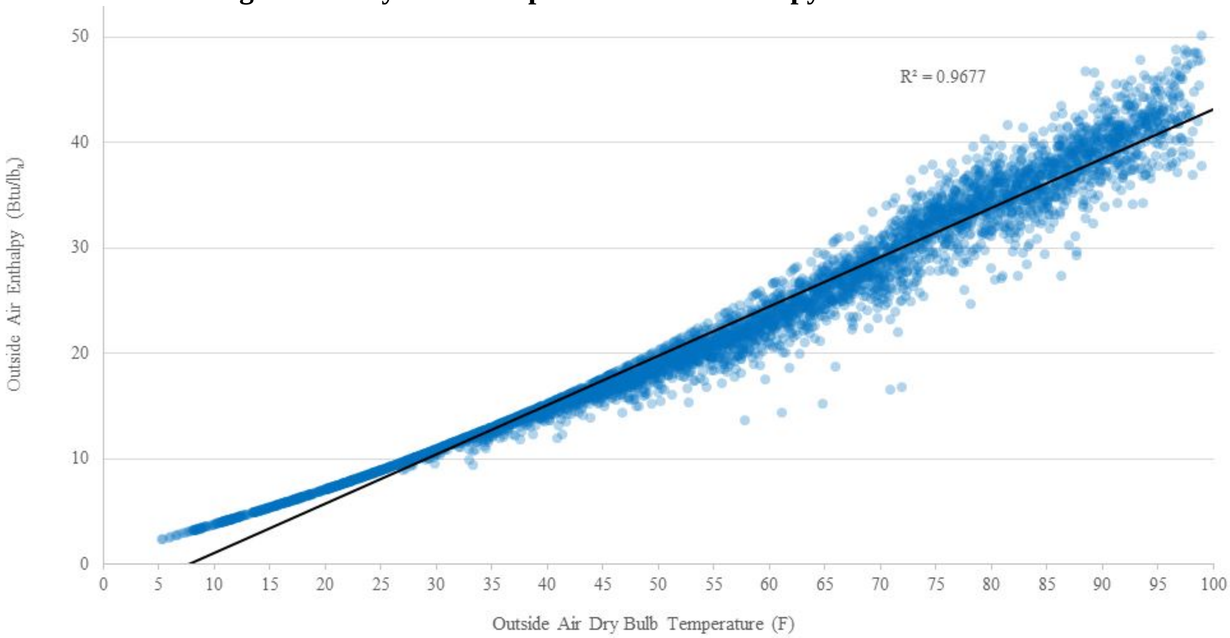


6.1.4.3 Outside Air Conditions

Another condition considered for statistical analysis was the energy content of outside air being used for ventilation and economizing. This could include effects from dry bulb temperature and wet bulb temperature (also measured as relative humidity or humidity ratio). While heating at the multizone hot deck coil is a sensible-only HVAC process and thus relates only to dry bulb temperature, the energy performance of the cooling coil is dependent on sensible and latent heat transfer and is therefore related to wet bulb temperature as well. As dry bulb temperature has a more universal effect on heating and cooling coil energy usage throughout the distribution of weather conditions as sensible ventilation loads, economizer-based loads, and conductive losses from the building, the relationship between dry bulb and humidity was examined to determine whether dry bulb temperature was a sufficient indicator of outside air conditions and energy content.

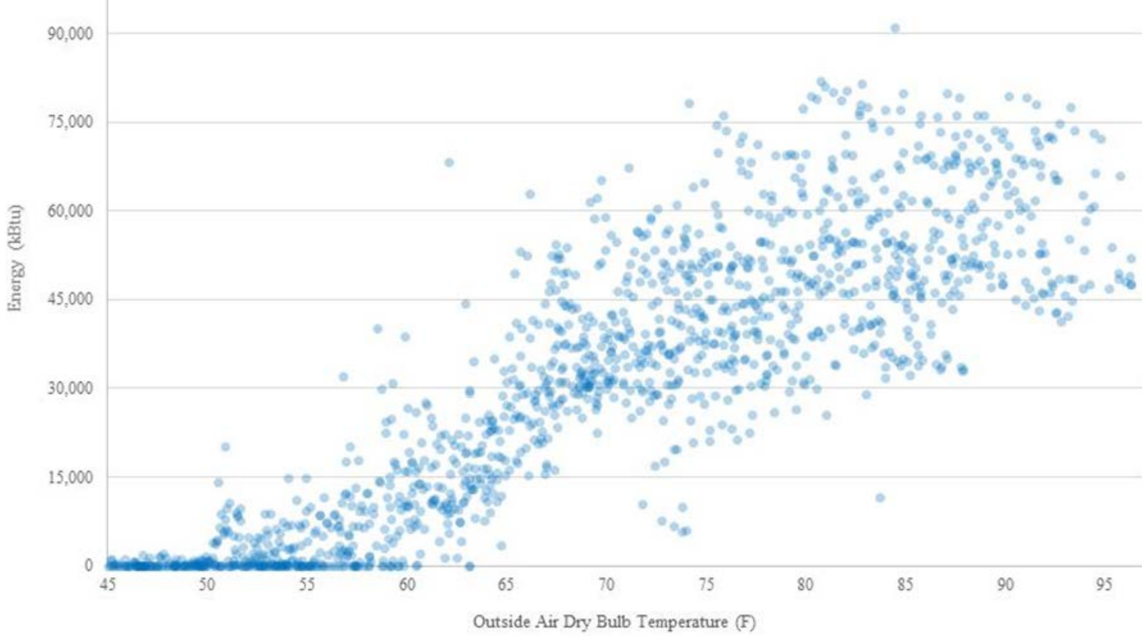
Based on the high correlation between total outside air enthalpy and dry bulb temperature for the data collected during the demonstration(see Figure 10 for an example), dry bulb temperature was deemed a sufficient indicator of outdoor air conditions. It's important to note that this may not be universally true for all climates, and applying the cooling energy savings findings in this study towards multizone units located in dramatically wetter and warmer climates (i.e., ASHRAE climate zones 1A or 2A) may understate the actual outside air energy content and thus understate the actual savings available.

Figure 10. Dry Bulb Temperature And Enthalpy Correlation At CERL



Once it was determined outside air (dry-bulb) temperature could be employed as the metric for outdoor air conditions, outside air temperature was examined to determine if it is a predominant energy driver. As expected, and as illustrated in Figure 11, outside air temperature indeed acts as a predominant energy driver for HVAC air-side systems providing outside air. Although the actual effect of temperature on energy use is dependent on many variables and not readily quantified in order to normalize savings based on temperature, statistically significant variations in energy savings due to outdoor air temperature can be prevented by ensuring that all three modes for a given multizone unit encountered similar ambient temperature distributions.

Figure 11. Outside Air Temperature and Chilled Water Energy Usage for CERL AHU-2



By plotting and visually inspecting a histogram of the weather data for each mode at CERL (Figure 12), it appears that weather will be significantly different across modes. To confirm this, a Kruskal-Wallis[4] test with a significance level of $\alpha = 0.05$ was used to statistically compare the data collected under each mode. The results (Table 9) show a near-zero probability of no statistically significant variation of weather data between the modes ($p << \alpha$). This indicates that further processing of the data is required to obtain comparable weather data sets.

[4] http://www.itl.nist.gov/div898/software/dataplot/refman1/auxillar/kruskwal.htm

Figure 12. Histogram Of Measured Dry Bulb Temperatures For CERL

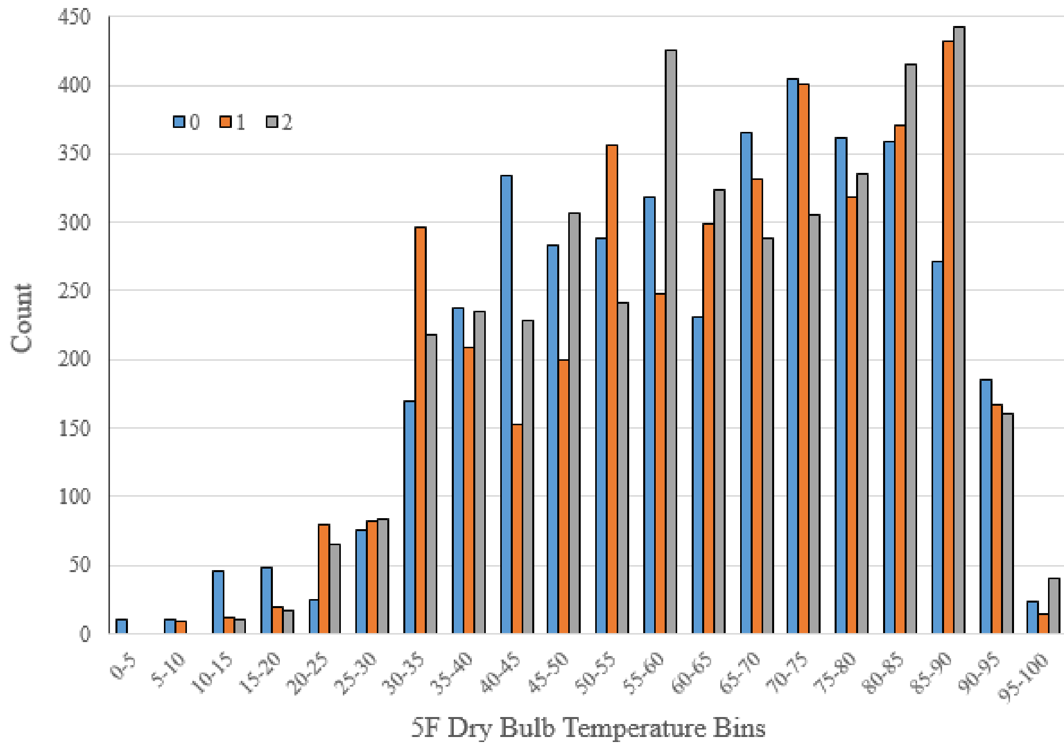


Table 9. Kruskal-Wallis Analysis Of Variability For Measured Temperatures At CERL

Mode	0	1	2
Temperature Rank Sums (T_j)	21,660,415	22,579,006	23,619,858
Group Size (n_j)	3,741	3,729	3,845
T_j^2/n_j	1.25E+11	1.37E+11	1.45E+11
$\Sigma\ T_j^2/n_j$	4.07E+11		
N ($\Sigma\ n_j$)	11,315		
H (12 x ($\Sigma\ T_j^2/n_j$ - 3(N+1))/ N x (N+1))	4,217.37		
Degrees of Freedom (df)	2		
Significance Level (α)	0.05		
Calculated Probability (p = Chiinv(α, df))	0.000		
Statistically Significant Variation? ($p<\alpha$)	Yes		

This analysis was repeated for Fort Bragg (Figure 13 and Table 10), and again indicated further processing was required.

Figure 13. Histogram Of Measured Dry Bulb Temperatures For Fort Bragg

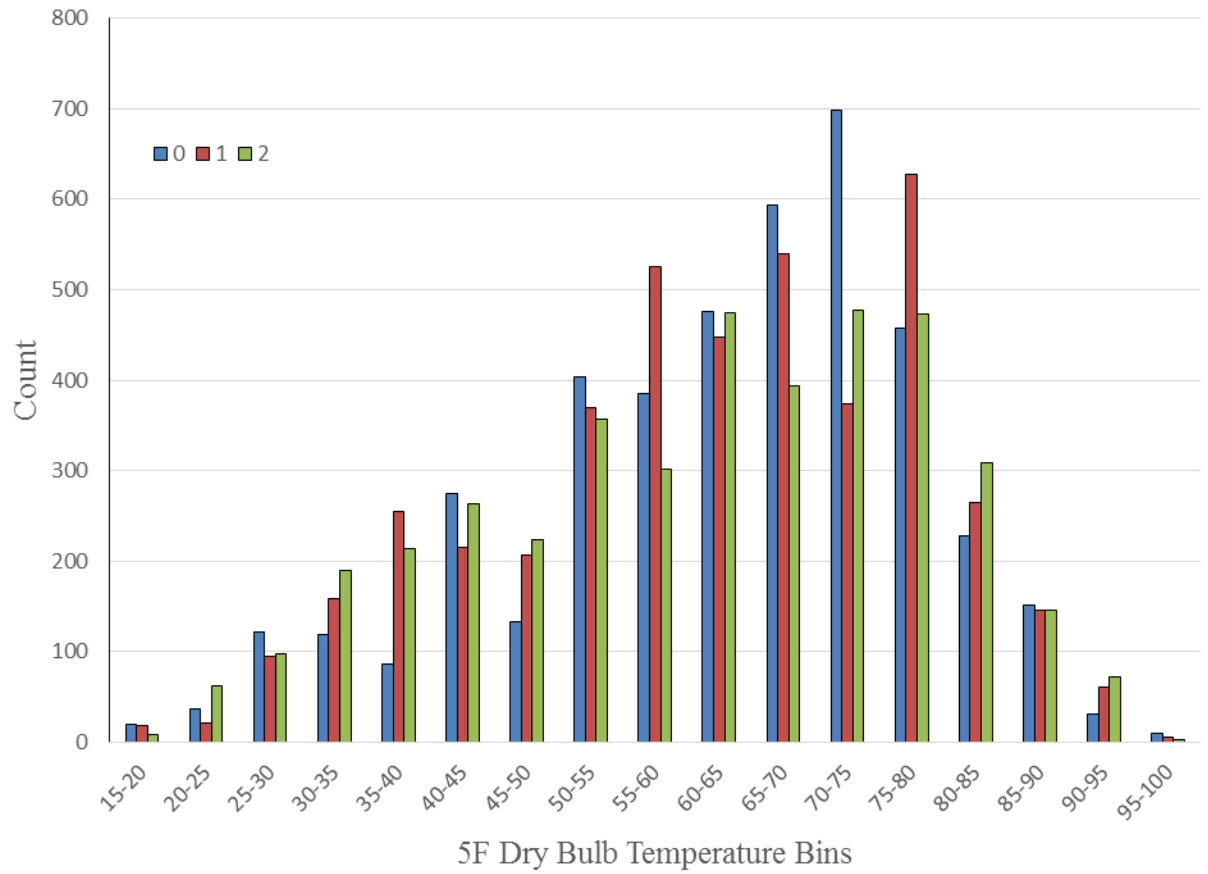


Table 10. Initial Kruskal-Wallis Analysis Of Variability For Measured Temperatures At Fort Bragg

Mode	0	1	2
Temperature Rank Sums (T_j)	23,503,583	24,556,588	22,857,925
Group Size (n_j)	3,524	4,326	4,059
T_j^2/n_j	1.57E+11	1.39E+11	1.29E+11
$\Sigma\ T_j^2/n_j$	4.25E+11		
N ($\Sigma\ n_j$)	11909		
H (12 x ($\Sigma\ T_j^2/n_j$ - 3(N+1))/ N x (N+1))	216.5814		
Degrees of Freedom (df)	2		
Significance Level (α)	0.05		
Calculated Probability (p = Chiinv(α, df))	0.000		
Statistically Significant Variation? ($p<\alpha$)	Yes		

To ensure that conclusions regarding energy performance would be independent of any outside air temperature variations between the operation modes, a refined data set was selected for each site that equalized the count of data points within each temperature bin (5° F temperature bins were used due to their common appearance in HVAC applications). For each temperature bin, the quantity of data points between modes was equalized by randomly removing excess points (relative to the mode with the lowest number of data points). Figure 14 illustrates the resulting consistency of outside air temperature data across modes at CERL. Figure 15 shows the outside air temperature distribution after equalizing for all the modes at Fort Bragg.

Figure 14. Histogram Of Processed Data For CERL

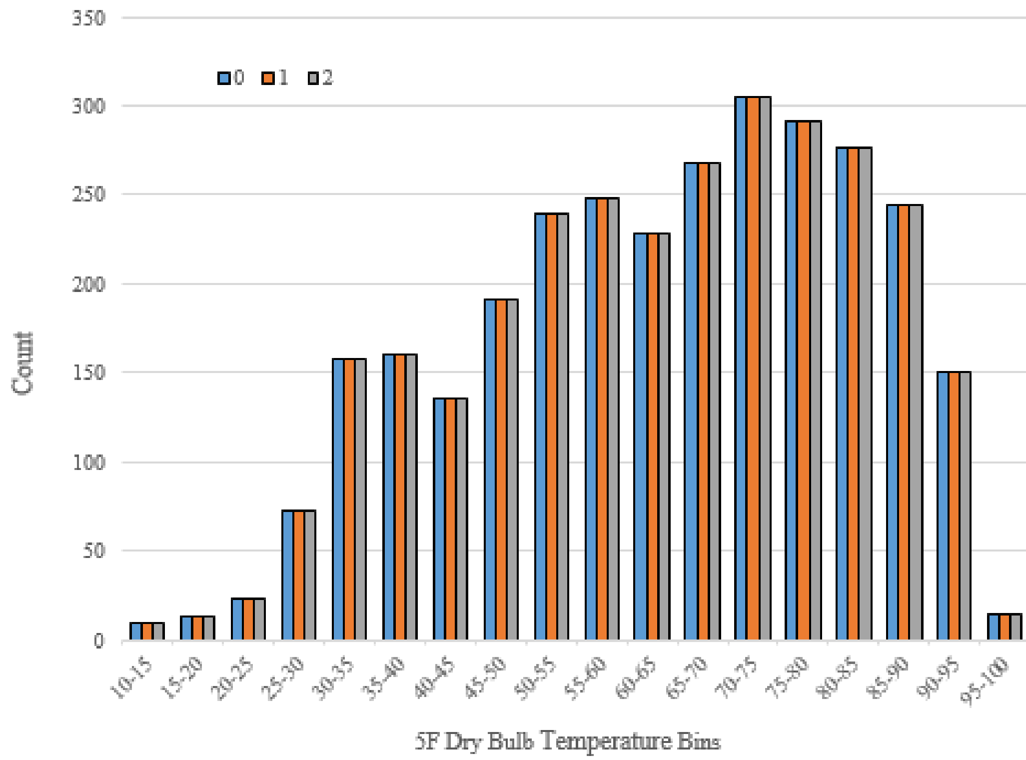
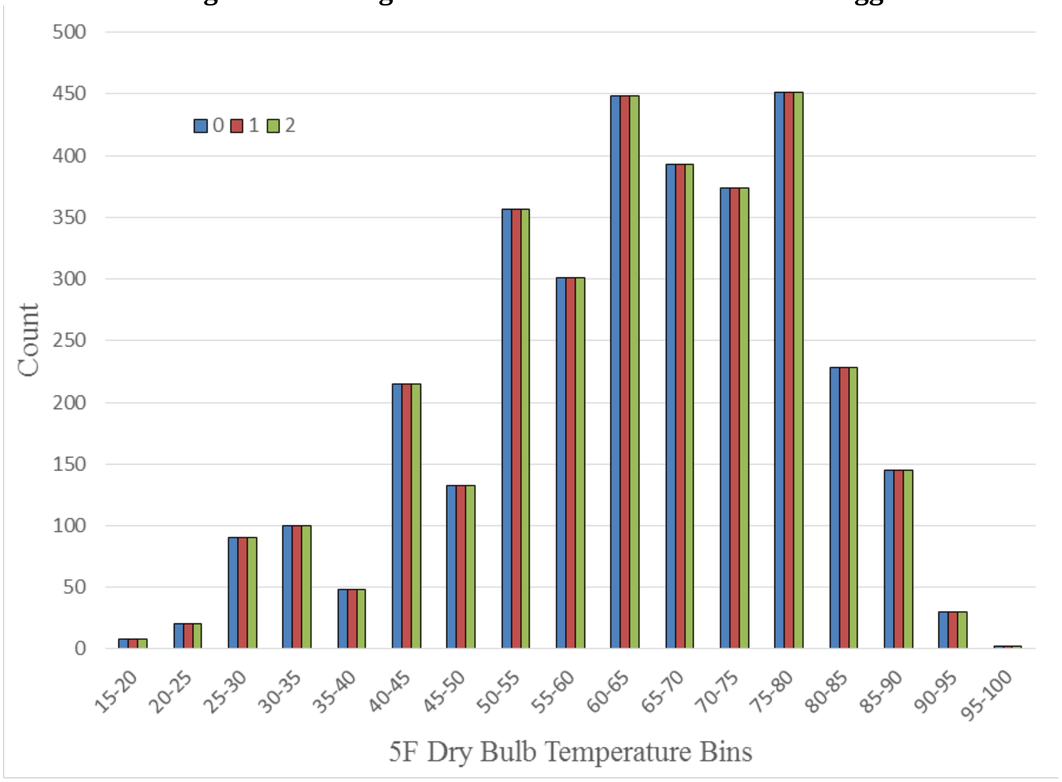


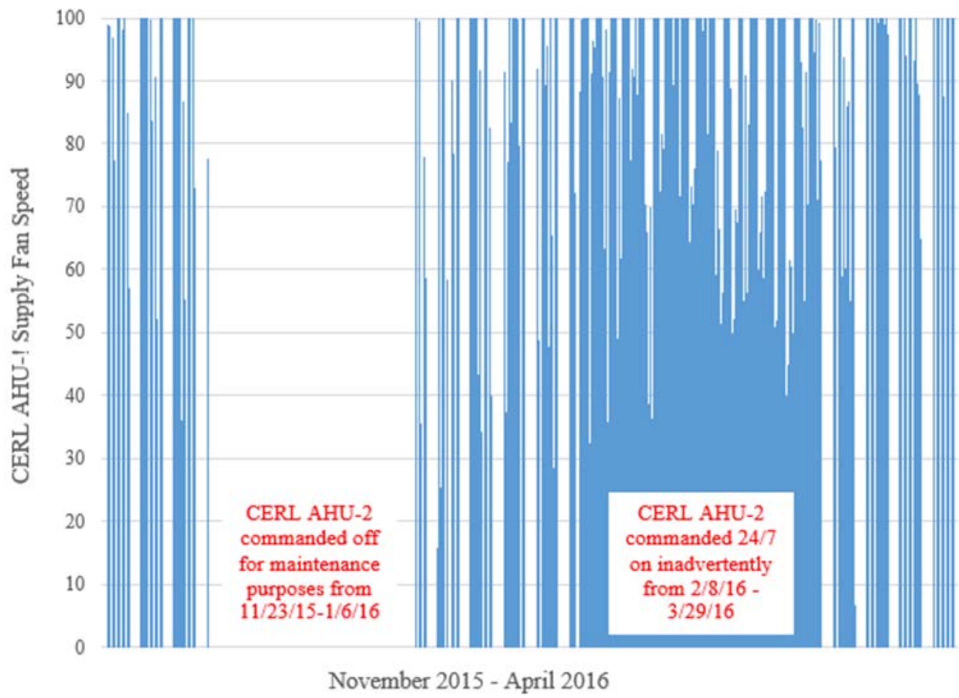
Figure 15. Histogram Of Processed Data For Fort Bragg



6.1.5 CERL Corrections Due To Other Operating Issues

CERL AHU-2 had a pair of 2-month long operational abnormalities: completely off in November/December of 2015 and the unit ran 24/7 in February/March of 2016 (instead of being scheduled off after hours) as shown in Figure 16.

Figure 16. Runtime Abnormalities For CERL AHU-2



In order to enable the analysis of CERL AHU-2, the data for this unit was processed further via:

1. Removal of 24/7 off times (no valuable energy usage data available)

2. Removal of the first two regularly scheduled hours (6:30am-8:30am) during 24/7-on periods in order to eliminate data that may be skewed with nighttime/weekend energy usage without any occupied zone loads or warm-up/cool-down energy usage that is reduced from already being at zone set point each morning. Two hours was selected as an acceptable threshold for negating the morning load problems based performance data of the system as shown in Figure 17 .

3. Repeat removal of data as necessary to reproduce equal instances of outdoor air temperature bin data across operation modes (see
4. Figure 18).

Figure 17. Zone Temperature Plot Used To Adjust CERL AHU-2 Runtimes

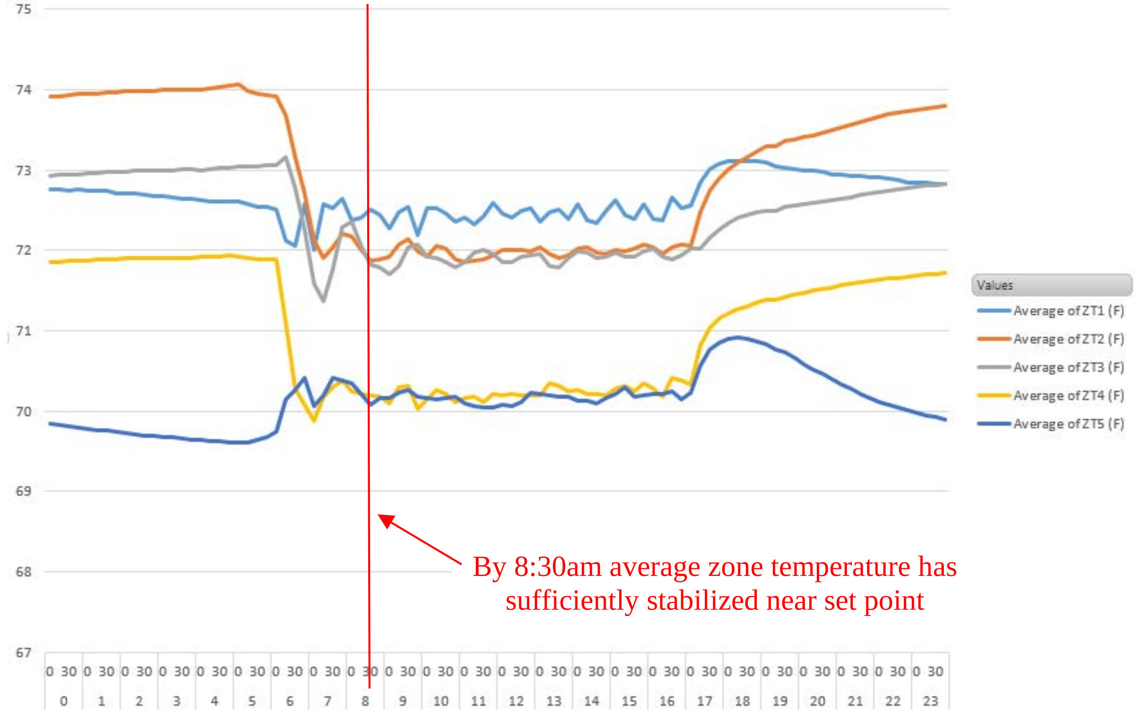
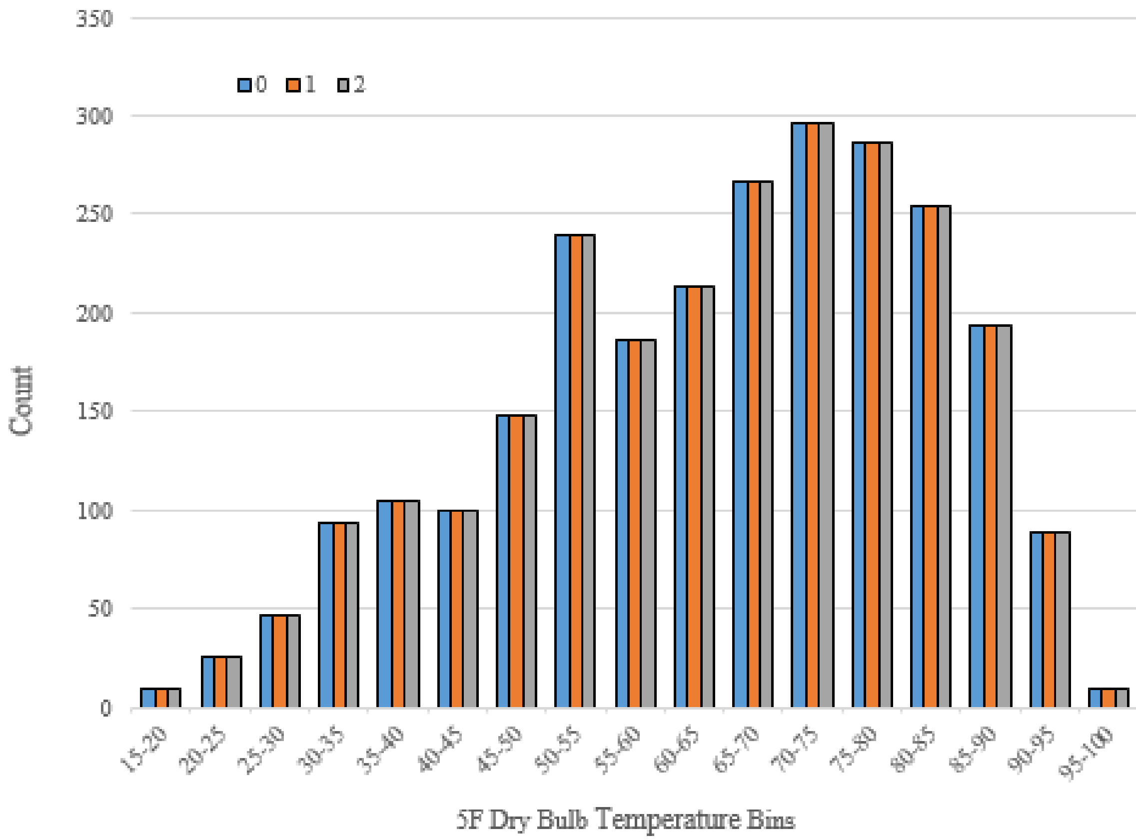


Figure 18. Histogram Of Outdoor Temperatures For Final CERL AHU-2 Data



Fort Bragg data for AHU-2 had a 2-month long operational abnormality, no data was recorded for most of January and all of February as shown in
Figure 19.As a result Fort Bragg AHU-2 was treated separately and not combined with AHU-1 and AHU-3, which resulted in a different weather temperature bin equalization for all modes, as seen in Figure 20.

Figure 19. Fort Bragg AHU-2 data loss due to UMCS being off

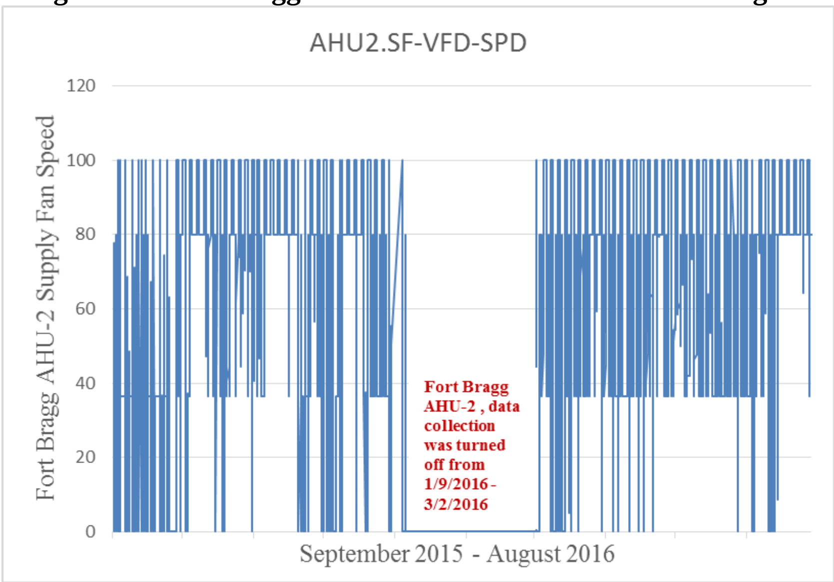
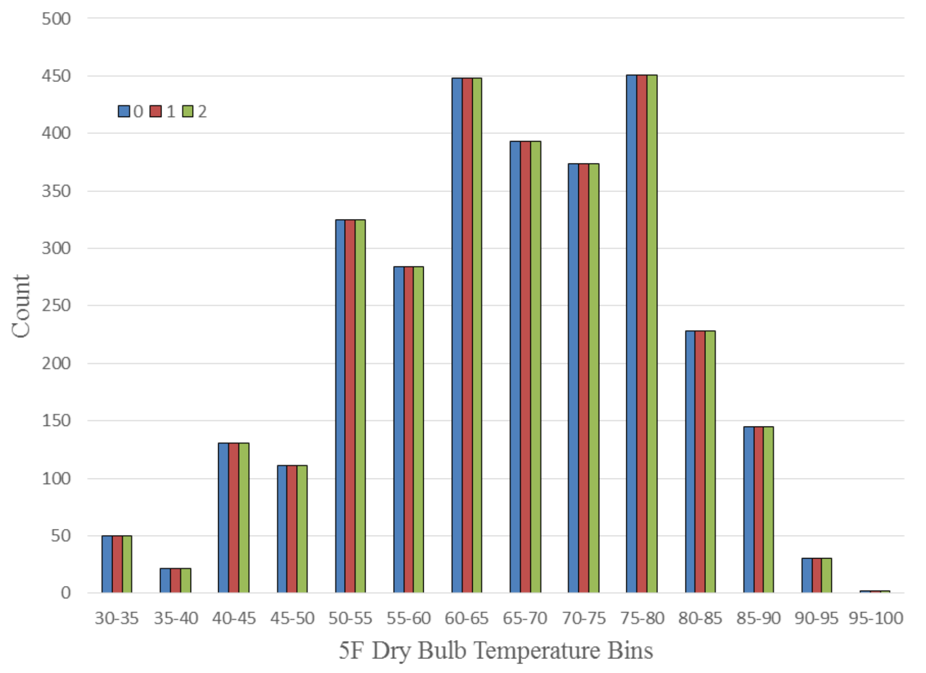


Figure 20. Histogram Of Outdoor Temperatures For Final Data For Fort Bragg AHU-2

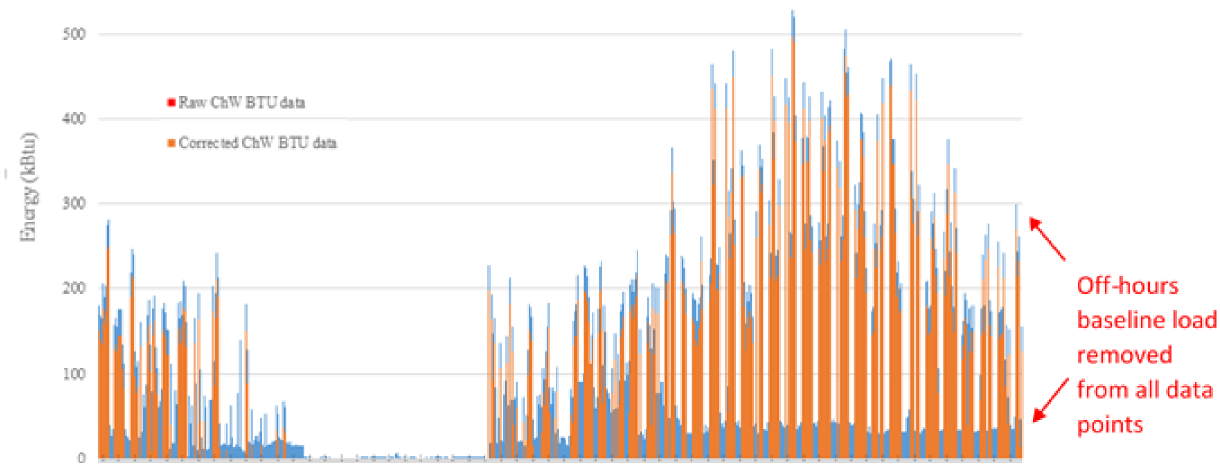


6.1.6 Correction For Known Data Inaccuracies For CERL Units

Once statistically identical datasets were established for AHU-1 and AHU-2 at CERL, the following corrections were made to energy performance variables:

1. adjusting non-zero heating or cooling energy at the BTU meter to zero when the air handler is off or coil valve is fully closed (0% HWV value)
2. subtracting the baseload BTU meter error readings off nonzero runtime data (see Figure 21)
3. Removing data from mode 0 when supply fan speed deviates from 100% (i.e., temporary maintenance-related overrides, equipment outages)
4. Outside air temperature jumps of more than 5F between 15-mintue interval data (all jumps were flagged and removed from the studies as part of the statistical analysis phase)

Figure 21. Raw And Corrected BTU Meter Readings For CERL AHU-1



6.1.7 Summary Of Data Processing

A summary of all the steps taken to process the data for analysis is shown in Table 11 (for Fort Bragg) and Table 12 (for CERL).

Table 11. Final Change Log For All Fort Bragg Adjustments

Change Number	Data Changed	Issue	Change Made
1	All data outside scheduled runtimes	No value to study	Data removed
2	Federal holidays where multizone units were commanded off	Data not useful while unit is off	Data removed
3	Data where units scheduled on but status/power shows as off	Data not useful while unit is off	Data removed
4	Random mode data with an excess of bin temperature instances relative to corresponding modes	Statistical analysis showed significant variation in temperature instances between modes	Data removed
5	All Fort Bragg AHU-2 off data in January-February of 2016	Data not useful while unit is off	Data removed
6	All Fort Bragg AHU-1 and 3 off data between February 1 2016 and February 15 2016	Data not useful while unit is off	Data removed
7	Additional Fort Bragg AHU-2 random mode data with an excess of bin temperature instances relative to corresponding modes	Removal of Fort Bragg AHU-2 data to mitigate scheduling errors could be reproducing statistically significant variation	Data removed
10	Any data containing or adjacent to outside air temperature jumps of more than 5F	Questionable changes in outside air temperature may be corrupting statistical analysis and energy performance summaries	(Data removed as part of statistical analysis step)
11	Any mode 0 data with fan speed less than 100%	Several instances of manual command of fan speed below 100% in mode 0 via VFD panel for maintenance purposes are skewing performance data	Data removed

Table 12. Final Change Log For All CERL Data Corrections And Adjustments

Change Number	Data Changed	Issue	Change Made
1	All data outside scheduled runtimes	No value to study	Data removed
2	Federal holidays where multizone units were commanded off	Data not useful while unit is off	Data removed
3	Data where units scheduled on but status/power shows as off	Data not useful while unit is off	Data removed
4	Random mode data with an excess of bin temperature instances relative to corresponding modes	Statistical analysis showed significant variation in temperature instances between modes	Data removed
5	All CERL AHU-2 data commanded 24/7-off in November-December of 2015	Data not useful while unit is off	Data removed
6	First 2 hours of morning data when CERL AHU-2 was commanded 24/7-off in February-March of 2016	Data not useful while unit is off	Data removed
7	Additional CERL AHU-2 random mode data with an excess of bin temperature instances relative to corresponding modes	Removal of CERL AHU-2 data to mitigate scheduling errors could be reproducing statistically significant variation	Data removed
8	Any HW or ChW BTU meter readings greater than 0 when coil valve is equal to 0% open	Slight and random BTU meter readings when coil valve closed are skewing mode performance data	BTU meter reading corrected to 0
9	All CERL AHU-1 ChW, AHU-2 ChW, and AHU-2 HW BTU meter data	Calibration errors discovered are overestimating BTU meter performance data	Calculated BTU meter baselines removed: 30 kBtuh from AHU-1 ChW, 55 kBtuh from AHU-2 ChW, 1.8 HW kBtu from AHU-2 HW
10	Any data containing or adjacent to outside air temperature jumps of more than 5F	Questionable changes in outside air temperature may be corrupting statistical analysis and energy performance summaries	(Data removed as part of statistical analysis step)
11	Any mode 0 data with fan speed less than 100%	Several instances of manual command of fan speed below 100% in mode 0 via VFD panel for maintenance purposes are skewing performance data	Data removed

6.1.8 Energy Performance For Processed Weather Data

After processing the data for statistical similarity and correcting data errors, the total fan and BTU meter energy usage for each mode was calculated for each system, and the reduction in energy use of Mode 1 and Mode 2 compared to Mode 0 was determined. These calculations were performed using the 5°F temperature bins to aid further analysis. Table 13 shows the results of this analysis for Mode 1 for AHU 1 at CERL as an example; tables showing results for all modes for all five systems are in Appendix D.

Table 13. CERL AHU-1 Energy Savings for the Processed Data Set for Mode 1

Temp. Bins (F)	Mode 0				Mode 1			
	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
10-15	47	-	1,922	2,081	24	-	517	598
15-20	60	-	2,582	2,786	24	-	250	331
20-25	106	-	4,282	4,645	74	-	2,620	2,873
25-30	340	42	12,741	13,942	309	-	10,544	11,598
30-35	730	244	17,390	20,126	604	33	15,304	17,398
35-40	762	105	25,717	28,423	679	19	20,655	22,989
40-45	639	64	17,375	19,620	486	60	15,042	16,759
45-50	896	-	24,647	27,704	573	-	16,331	18,287
50-55	1,127	361	21,905	26,114	799	90	14,317	17,132
55-60	1,159	3,702	13,812	21,471	881	2,413	10,653	16,072
60-65	1,070	12,050	13,551	29,254	655	10,797	7,798	20,829
65-70	1,253	35,758	6,545	46,581	681	24,651	5,760	32,733
70-75	1,413	48,872	3,848	57,541	1,024	46,729	1,961	52,183
75-80	1,345	58,232	1,245	64,068	1,071	49,046	839	53,541
80-85	1,262	68,836	331	73,473	1,009	51,985	268	55,698
85-90	1,113	67,616	149	71,566	994	51,355	-	54,748
90-95	686	48,008	-	50,349	648	43,018	-	45,230
95-100	63	4,086	-	4,302	60	4,103	-	4,309
Total	14,071	347,976	168,044	564,044	10,593	284,299	122,857	443,309
Reduction (relative to mode 0)					24.7%	18.3%	26.9%	21.4%

The results of this analysis for all five demonstration systems is summarized in Table 14. For each system the variable volume modes achieved significant energy reduction compared to the constant volume modes, exceeding the goal of 10% energy savings.

Table 14. Energy Savings for the Processed Data Set

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v mode 0
CERL 1	564,044	443,309	21.4%	431,444	23.5%
CERL 2	554,146	209,530	62.2%	207,132	62.6%
BRAGG 1	34,614	18,658	46.1%	17,829	48.5%
BRAGG 2	31,517	25,469	19.2%	25,502	19.1%
BRAGG 3	39,258	27,471	30.0%	27,730	29.4%

6.1.9 Energy Performance For 2016 Weather-Normalized Data

The data processing steps described above resulted in a final data set that represents portions of the year and are not fully reflective of the actual year's outside air temperature distribution. Further analysis was conducted to map these savings percentages by bin onto the study year's recorded bin data. By calculating the savings per bin hour from the processed data and multiplying these savings by the number of bin hours actually recorded for the year, the predicted energy savings for the year is calculated. Table 15 shows the results of this analysis for AHU-1 at CERL for Mode 0 and Mode 1; tables showing results for all modes for all five systems are in Appendix D. Table 16 summarizes the results of this analysis for all five demonstration systems. This adjusted performance data represents a slight overall increase in the mode 1 and mode 2 energy savings (an additional 1.6% and 2.0%, respectively for CERL and 0.6% and 1.1% for Fort Bragg).

Table 15. CERL AHU-1 Energy Savings for the 2016 Weather-Normalized Data Set for Mode 1

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
10-15	20	92	0	3,805	4,119	47	0	1,023	1,184
15-20	24	111	0	4,825	5,205	44	0	468	619
20-25	45	209	0	8,432	9,147	146	0	5,159	5,658
25-30	64	300	37	11,245	12,304	272	0	9,306	10,235
30-35	174	803	269	19,128	22,137	664	36	16,833	19,137
35-40	173	824	113	27,813	30,740	734	20	22,339	24,863
40-45	179	846	85	23,012	25,985	643	79	19,922	22,196
45-50	196	920	0	25,330	28,471	589	0	16,784	18,793
50-55	215	1,009	323	19,604	23,371	715	81	12,813	15,332
55-60	229	1,070	3,415	12,742	19,808	812	2,226	9,828	14,827
60-65	189	885	9,965	11,206	24,191	541	8,929	6,448	17,224
65-70	199	930	26,524	4,855	34,552	505	18,285	4,272	24,280
70-75	227	1,049	36,300	2,858	42,739	760	34,708	1,457	38,760
75-80	207	957	41,431	886	45,583	762	34,896	597	38,094
80-85	225	1,029	56,126	270	59,908	823	42,387	218	45,414
85-90	277	1,263	76,703	170	81,184	1,128	58,257	0	62,106
90-95	131	596	41,742	0	43,777	564	37,404	0	39,327
95-100	23	102	6,579	0	6,926	97	6,606	0	6,937
Total	2,795	12,996	299,613	176,180	520,148	9,847	243,913	127,465	404,987
Reduction (relative to mode 0)						24.2%	18.6%	27.7%	22.1%

Table 16. Energy Savings for the 2016 Weather-Normalized Data

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v. mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v. mode 0
CERL 1	520,148	404,987	22.1%	396,660	23.7%
CERL 2	587,346	224,099	61.8%	208,389	64.5%
BRAGG 1	129,043	69,906	45.8%	66,015	48.8%
BRAGG 2	123,571	94,495	23.5%	94,468	23.6%
BRAGG 3	144,691	101,115	30.1%	100,932	30.2%

6.1.10 Energy Performance For Historic Weather Normalized Data

The analysis described above provides an estimate of energy savings for the demonstration year, but does not necessarily represent the energy savings in a **typical** year. Recognizing that the weather encountered during the study period may not be sufficiently representative of typical temperature patterns, nearby weather station averages were leveraged to normalize energy performance results against typical heating and cooling conditions to provide a more general evaluation for expected system performance.

Table 17 shows 23-year average bin hour data (1973-1996) downloaded from the National Climate Data Center (NCDC) for Champaign, IL weather station number 725315. The last column adjusts the daytime bin hours (8am-4pm) to account for the actual operation schedule of CERL's multizone units (5 days per week, 10.75 hours per day).

Table 17. Historical Temperature Bin Data for CERL

Temperature Bins (°F)	Bin Hours (12am-8am)	Bin Hours (8am-4pm)	Bin Hours (4pm-12am)	Total Annual Bin Hours	Adjusted Bin Hours
-10--5	9	4	5	18	4
-5-0	12	4	7	23	4
0-5	34	15	21	70	13
5-10	45	21	32	98	20
10-15	56	38	49	143	36
15-20	70	56	67	193	53
20-25	120	82	105	307	79
25-30	183	123	159	465	118
30-35	287	207	277	771	198
35-40	253	222	253	728	213
40-45	208	176	200	584	169
45-50	213	167	193	573	160
50-55	237	173	199	609	166
55-60	252	179	202	633	171
60-65	292	198	238	728	189
65-70	292	208	255	755	200
70-75	234	248	262	744	238
75-80	97	295	207	599	283
80-85	23	259	120	402	249
85-90	3	167	51	221	160
90-95	0	64	15	79	60
95-100	0	14	3	17	12
Total	2,920	2,920	2,920	8,760	2,795

For Fort Bragg, the last ten years' worth of weather data were used to construct the same average bin hour data (2006-2016) shown in Table 18, from NCDC for Pope AFB, NC, weather station number 723030.

Table 18. Historical Temperature Bin Data for Fort Bragg

Temperature Bins (°F)	Bin Hours (12am-8am)	Bin Hours (8am-4pm)	Bin Hours (4pm-12am)	Total Annual Bin Hours	Adjusted Bin Hours
5-10	0	1	0	1	1
10-15	1	3	0	3	3
15-20	6	14	0	20	15
20-25	29	35	6	70	38
25-30	70	71	22	163	79
30-35	128	138	40	306	154
35-40	218	194	93	505	216
40-45	231	219	144	593	244
45-50	188	185	167	541	206
50-55	264	256	235	754	285
55-60	251	257	225	733	286
60-65	299	318	254	871	354
65-70	409	391	297	1097	435
70-75	384	352	295	1032	392
75-80	315	306	386	1007	340
80-85	103	121	324	548	135
85-90	21	49	269	339	54
90-95	1	12	120	133	13
95-100	0	1	38	39	1
100-105	0	0	4	4	0
Total	2,920	2,920	2,920	8,760	3,250

Figure 22 shows these 2,795 adjusted bins hours plotted against the final distribution of temperature data recorded at CERL during the study period and illustrates the value in normalizing energy performance results for average weather. Since the study year was warmer on average than the NCDC record, there are lower temperature bins that the study was not able to provide usage or savings data for. Normalized performance data for the first four temperature bins shown Figure 22 was estimated based on linear projection of fan, cooling, and heating energy in each mode. This projected data represents only 1.5% of the 2,795 annual bin hours for CERL.

Figure 22. Processed Temperature Data Versus Historical Temperature Data at CERL

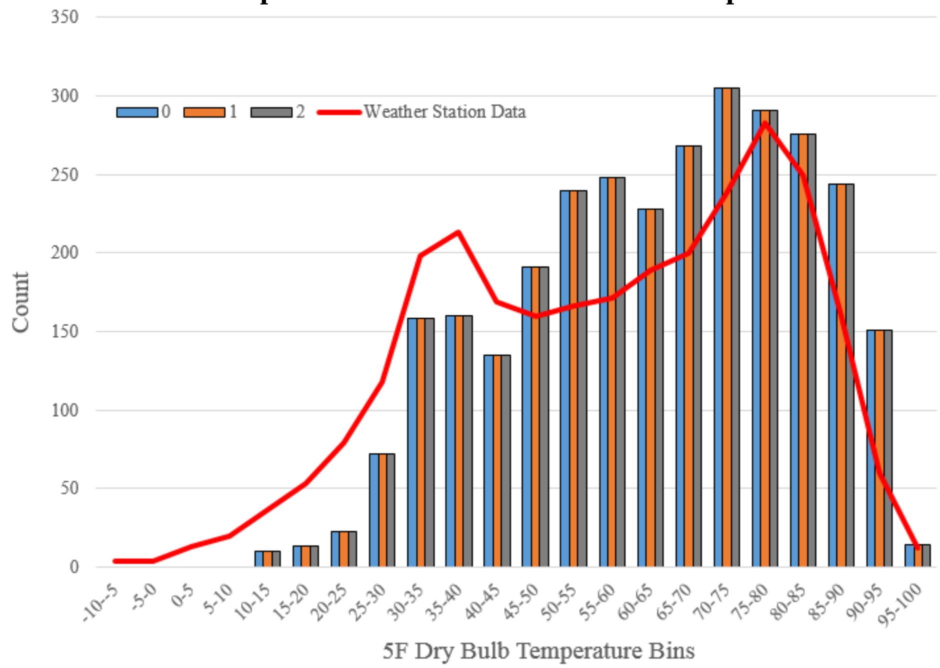
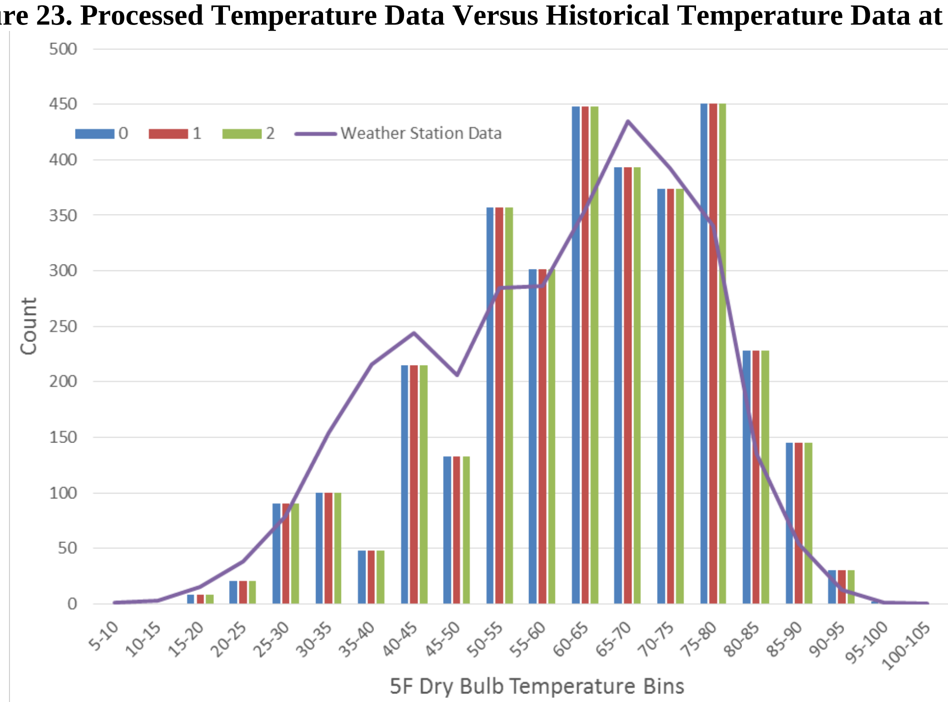


Figure 23 shows 3,250 adjusted bins hours plotted against the final distribution of temperature data recorded at Fort Bragg during the study period. Again, the study year was warmer on average than the NCDC data, so there are lower temperature bins that the study was not able to provide usage or savings data for and a linear projection was used for these bins. This projected data represents only 0.1% of the 3,250 annual bin hours for Fort Bragg.

Figure 23. Processed Temperature Data Versus Historical Temperature Data at CERL



As with the process for normalizing to the 2016 weather data, the per-bin savings were used to calculate the expected typical energy savings per year based on the historical data. Table 19 shows the results of this analysis for AHU-1 at CERL for Mode 0 and Mode 1; tables showing results for all modes for all five systems are in Appendix D. Table 20 summarizes the results of this analysis for all five demonstration systems

Table 19. CERL AHU-1 Mode 1 Energy Savings for the Historical Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
-10--5	4	19	0	1,029	1,093	11	0	544	581
-5-0	4	19	0	974	1,037	11	0	517	554
0-5	13	60	0	2,987	3,193	36	0	1,592	1,716
5-10	20	93	0	4,320	4,636	57	0	2,314	2,509
10-15	36	168	0	6,920	7,493	86	0	1,861	2,153
15-20	53	243	0	10,528	11,357	97	0	1,020	1,351
20-25	79	365	0	14,708	15,954	255	0	8,998	9,869
25-30	118	556	68	20,882	22,849	506	0	17,281	19,008
30-35	198	915	306	21,793	25,221	757	41	19,178	21,803
35-40	213	1,015	139	34,236	37,838	903	25	27,497	30,604
40-45	169	800	80	21,752	24,562	608	75	18,831	20,980
45-50	160	750	0	20,647	23,207	480	0	13,681	15,319
50-55	166	780	250	15,151	18,062	552	62	9,902	11,850
55-60	171	799	2,553	9,524	14,805	607	1,664	7,345	11,082
60-65	189	887	9,989	11,233	24,250	543	8,950	6,464	17,266
65-70	200	935	26,685	4,884	34,762	508	18,396	4,298	24,428
70-75	238	1,102	38,136	3,003	44,901	799	36,464	1,530	40,720
75-80	283	1,308	56,631	1,211	62,307	1,042	47,698	816	52,070
80-85	249	1,138	62,102	298	66,286	911	46,900	242	50,249
85-90	160	730	44,339	98	46,928	652	33,675	0	35,900
90-95	60	273	19,076	0	20,006	258	17,093	0	17,972
95-100	12	54	3,503	0	3,687	52	3,517	0	3,693
Total	2,795	13,009	263,857	206,177	514,434	9,729	214,560	143,911	391,676
Reduction (relative to mode 0)						25.2%	18.7%	30.2%	23.9%

Table 20. Energy Savings for the Historic Weather-Normalized Data Set

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v. mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v. mode 0
CERL 1	514,434	391,676	23.9%	367,642	28.5%
CERL 2	581,926	257,910	55.7%	233,881	59.8%
BRAGG 1	123,991	66,135	46.7%	61,084	50.7%
BRAGG 2	118,266	88,423	25.2%	88,411	25.2%
BRAGG 3	138,899	94,775	31.8%	94,086	32.3%

This historical weather-normalized data was used for the analysis of performance and cost.

6.1.11 Total Energy Performance

The previous analysis addressed the energy consumption and savings at the air handler. In order to identify the total energy usage and savings, upstream system efficiencies were considered so that the final energy savings as measured at the air handler could be translated into expected energy savings as measured at the utility meter.

Based on equipment and system configurations at CERL, the following efficiency adjustments were made prior to life cycle cost analysis:

1. *Variable Frequency Drive (VFD) efficiency:* UMCS fan power data used in this study represents electrical load of the fan systems at the output of the VFD panel. This data already captures downstream inefficiencies from fan, belt, and motor losses, however a correction factor is required for the VFD itself to calculate for the input electricity delivered to the VFD that would be registered by the utility meter. Figure 24 is a summary cut sheet from a CERL VFD that identifies this efficiency as 97%.

Figure 24. VFD Electrical specifications

E-Flex™ Enclosed Drive Controller
Specifications

8839DB0701
02/2007

Specifications

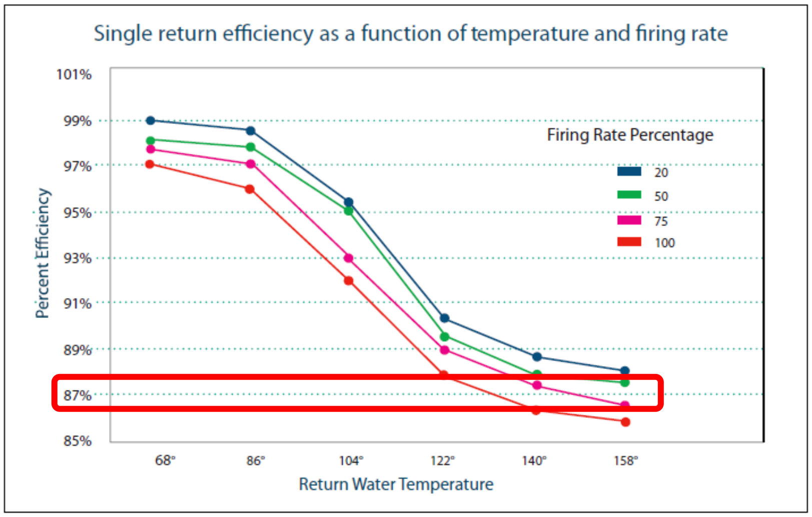
Electrical

Input voltage	208 Vac ±10%, 230 Vac ±10%, 460 Vac ±10%
Displacement power factor	98% through speed range
Input frequency	60 Hz ±5%
Output voltage	Three -phase output, maximum voltage equal to input voltage
Galvanic isolation	Galvanic isolation between power and control (inputs, outputs, and power supplies)
Frequency range of power converter	0.1 to 500 Hz (factory setting of 60 Hz)
Torque/overtorque	Variable Torque: 110% of nominal motor torque for 60 s
Current (transient)	Variable Torque: 110% of controller rated current for 60 s
Switching frequency	Selectable from 0.5 to 16 kHz on 1–100 hp VT controllers Above 8 kHz, select the next largest drive controller **Factory setting**: 8 kHz for 208 Vac, 230 Vac and 1–100 hp @460 Vac
Speed reference	AI1: 0 to +10 Vac, Impedance = 30 kW, can be used for speed potentiometer, 1–10 kΩ AI2: **Factory setting**: 4 to 20 mA, Impedance = 242 Ω Factory modification J09 allows 0–10 Vdc reference signal to AI2
Factory resolution in analog reference	0.1 for 100 Hz (11 bits)
Speed regulation	V/f control: equal to the motor's rated slip SLFV (sensorless flux vector): 10% of motor's rate slip from 20% to 100% of nominal motor torque
Efficiency	97% of full load typical
Reference sample time	2 ms ±0.5 ms
Acceleration and deceleration ramps	0.1 to 999.9 seconds (definition in 0.1 s increments)
Drive controller protection	Thermal protection of power converter Phase loss of AC mains Circuit breaker rated at 100 kAIC
Motor protection	Class 10 electronic overload protection Class 20 electromechanical overload protection with bypass (Class10 electromechanical for 1 hp at 460 Vac)
Graphic display terminal	Self diagnostics with fault messages in three languages; also refer to the programming manual supplied on the CD ROM W817574030111 which ships with the power converter, and the instruction bulletin, Graphic Display Terminal VW3A1101, bulletin number 1760643 (VT)

2. *Hot water system losses:* Building natural gas consumption required to provide the heating energy measured at the hot deck BTU meter is dependent on distribution losses through the piping network, cycling losses at the boiler from pre- and post-purge sequences, and combustion efficiency of the burners themselves. Based on observed system characteristics, conservative engineering assumptions, and Figure 25 (CERL boiler combustion efficiency curves), the distribution, cycling, and combustion efficiencies were estimated at 90%, 85%, and 87%, respectively. Thus, a total hot water system efficiency of 67% was applied. In this

study, hot water pump speeds were not dependent on load changes at coil valves and thus no additional savings from hot water pump usage were considered.

Figure 25. Condensing Boiler Combustion Efficiencies



3. *Chilled water system losses*: Similarly, electrical energy required to meet cooling demands at the chilled water coil BTU meter is dependent on network losses and chiller energy efficiency ratios. Using Figure 26 for general rules of thumb to estimate electrical load required for water-cooled chillers per ton of cooling and based on compressor types and sizes in use, an efficiency ratio of 0.64 kW/ton was applied. Distribution losses were also estimated at 10%, however no additional factors were considered for chilled water pump, cooling tower, or ice tank systems.

Figure 26. Chiller efficiency factors

Efficiency Recommendations – Water Cooled Chillers		
Compressor Type and Capacity	Part Load Optimized Chillers	
	Recommended[a] IPLV (kW/ton)	Best Available[a] IPLV (kW/ton)
Centrifugal (150 - 299 tons)	0.52 or less	0.47
Centrifugal (300 - 2,000 tons)	0.45 or less	0.38
Rotary Screw >= 150 tons	0.49 or less	0.46
Compressor Type and Capacity	Full Load Optimized Chillers	
	Recommended Full Load[d] (kW/ton)	Best Available Full-Load[d] (kW/ton)
Centrifugal (150 - 299 tons)	0.59 or less	0.50
Centrifugal (300 - 2,000 tons)	0.56 or less	0.47
Rotary Screw >= 150 tons	0.64 or less	0.58

Detailed information for Fort Bragg's equipment and configuration was not available, but the efficiency values calculated for CERL are considered typical, and therefore the CERL efficiency values were used for Fort Bragg. Table 21 shows the calculated total upstream energy use for each of the demonstrated systems based on the historic weather-normalized energy savings of each system. These values are used for the economic analysis in Section 7.

Table 21. Estimated Total Upstream Energy Savings for the Historic Weather-Normalized Data Set

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v. mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v. mode 0
CERL 1	406,836	292,397	28%	235,475	42%
CERL 2	787,517	312,814	60%	281,540	64%
BRAGG 1	70,953	26,027	63%	30,521	57%
BRAGG 2	62,962	43,953	30%	46,663	26%
BRAGG 3	79,722	47,828	40%	48,550	39%

6.2 COST ANALYSIS SUMMARY

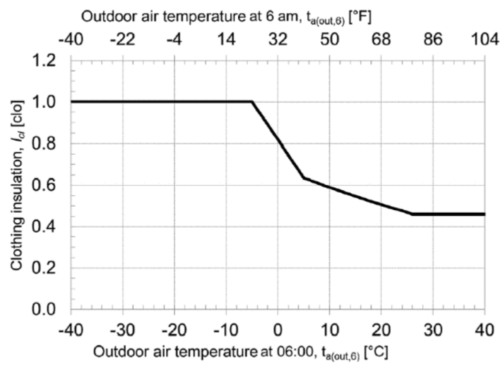
Cost analysis is described in Section 7.

6.3 COMFORT ASSESSMENT

The value of the multizone retrofit method is partially dependent upon the ability of the post-retrofit AHU to maintain indoor environmental quality including thermal comfort. The expectation was that thermal comfort would be equal to or better than the pre-retrofit AHU. The comfort performance metric used in our assessment was based on criteria defined in ASHRAE Standard 55 (2010) "Thermal Environmental Conditions for Human Occupancy".

ASHRAE Standard 55 defines six condition variables as listed in Table 22 that impact occupant comfort. ASHRAE Standard 55 also indicates that a survey of occupants is an acceptable method to determine occupant thermal comfort. Performing a survey throughout the 1-year duration of the test with the AHUs switching between the three modes daily would have been impractical if not impossible so only a numeric analysis of comfort was used.

Table 22. ASHRAE Standard 55 Occupant Comfort Variables

Metabolic Rate (met)	1.1
Clothing level (clo)	Varies with outdoor air temperature: 
Zone Air Temperature (ºF)	From UMCS Data
Zone Relative Humidity (%RH)	From UMCS Data
Air Velocity (fpm)	0 (still air)
Mean Radiant Temperature (ºF)	Zone Air Temperature

6.3.1 Thermal Comfort Analysis

Based on ASHRAE Standard 55 the six comfort condition variables listed in Table 22 were used to calculate thermal comfort in the spaces served by the retrofitted AHUs at Fort Bragg and CERL. The comfort calculation was performed at 15-minute time intervals for each of the three operating modes.

An additional measurement of thermal comfort, the zone temperature deviation from the temperature set point, was also calculated at 15-minute time intervals for each of the 3 operating modes.

6.3.1.1 Fort Bragg

Figure 27 shows the temperature and relative humidity data collected during the study for Fort Bragg AHU-2 Zone 5 plotted on a Psychrometric Chart. The figure is specific to AHU-2 Zone 5 and is indicative of the other AHUs and their respective zones' comfort results. The straight lines in the chart depict the ASHRAE comfort zone. This corresponds to winter and summer 'clo' (clothing) level where the two red lines 'bracket' the winter clothing level (clo=1) comfort zone and the 2 blue lines bracket to summer closing level (clo=0.46) comfort zone. In each case the metabolic rate was 1.1. The diamond symbol represents the zone temperature set point employed by Fort Bragg (75°F).

The 75°F zone setpoint remains fixed for summer and winter periods of operation therefore likely results in periods of discomfort (irrespective of the operating mode 0, 1, or 2) even though it appears fairly well centered between the winter and summer comfort zones.

The total amount of time each zone was in the comfort zone shown in table in Figure 22. The table suggests modes 1 and 2 yielded a somewhat less comfortable thermal environment than mode 0.

Table 24 provides an indication of how well each zone's temperature setpoint is maintained in each mode. The calculation methodology consisted of the absolute value of the difference between zone temperature and setpoint at each 15 minute interval over the (roughly 1 year) duration of the test and then all of these values were averaged. The results show that modes 1 and 2 do not average significantly further from setpoint than mode 0.

Figure 27. Representative Zone Thermal Comfort for Fort Bragg AHU-2, Zone 5

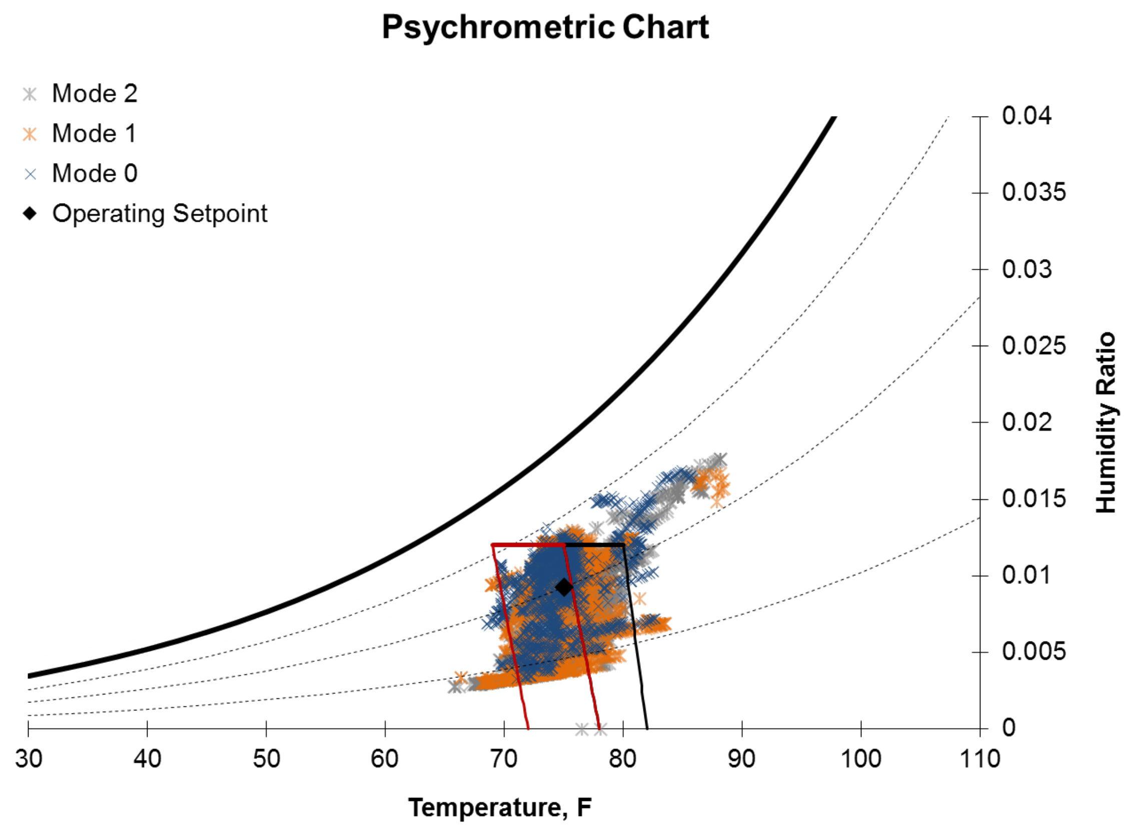


Table 23. Time Spent Within The Comfort Zone For Each AHU, Zone And Mode For Fort Bragg

	AHU 1			AHU 2			AHU 3		
	MODE 0	MODE 1	MODE 2	MODE 0	MODE 1	MODE 2	MODE 0	MODE 1	MODE 2
Zone 1	35.1%	30.0%	25.9%	60.8%	56.0%	56.9%	31.7%	49.0%	47.7%
Zone 2	38.8%	34.9%	31.7%	35.7%	34.0%	32.6%	36.0%	58.5%	57.3%
Zone 3	44.4%	35.5%	31.4%	93.7%	89.4%	89.4%	26.3%	60.2%	61.8%
Zone 4				60.6%	57.3%	55.1%	25.8%	41.4%	41.7%
Zone 5				31.8%	22.6%	27.7%	31.0%	53.9%	51.3%
Zone 6				80.8%	69.6%	69.5%	57.8%	53.9%	54.5%
Zone 7				67.4%	63.0%	60.9%	38.7%	65.1%	62.3%
Zone 8				60.9%	62.4%	56.9%	21.2%	53.9%	46.9%
Zone 9				54.2%	44.7%	46.5%			
Total	39.4%	33.5%	29.7%	60.6%	55.5%	55.0%	33.6%	54.5%	52.9%
Delta from Mode 0		-6.0%	-9.8%		-5.2%	-5.6%		20.9%	19.4%

Note: Systems have different numbers of zones. Empty entries indicate that zone does not exist.

Table 24. Difference (ºF) Between Actual Zone Temperature And Set Point For Fort Bragg AHUs

	AHU 1			AHU 2			AHU 3		
	MODE 0	MODE 1	MODE 2	MODE 0	MODE 1	MODE 2	MODE 0	MODE 1	MODE 2
Zone 1	2.12	2.00	2.29	1.85	1.90	2.03	2.21	2.07	2.13
Zone 2	1.98	1.96	2.18	1.62	1.74	1.89	2.20	2.02	2.35
Zone 3	2.22	2.14	2.28	14.42	13.74	13.96	2.45	3.50	3.94
Zone 4				2.35	2.08	2.34	2.19	1.96	2.04
Zone 5				1.53	1.42	1.78	2.18	2.38	2.61
Zone 6				3.04	2.56	2.77	5.10	5.69	4.76
Zone 7				2.74	2.51	2.58	2.10	2.06	2.29
Zone 8				2.73	2.46	2.42	2.38	2.17	2.38
Zone 9				2.31	2.08	2.43			
Total	2.10	2.03	2.25	5.96	5.80	5.96	2.29	2.53	2.81
Delta from Mode 0		-0.07	0.15		-0.17	-0.01		0.24	0.52

Note: Systems have different numbers of zones. Empty entries indicate that zone does not exist.

6.3.1.2 CERL

Figure 28 shows the temperature and relative humidity data collected during the study for CERL AHU-1 Zone 2 plotted on a Psychrometric Chart. The figure is specific to AHU-2 Zone 5 and is indicative of the other AHUs and their respective zones' comfort results. The straight lines in the chart depict the ASHRAE comfort zone. This corresponds to winter and summer 'clo' (clothing) level where the two red lines 'bracket' the winter clothing level (clo=1) comfort zone and the 2 blue lines bracket to summer

closing level (clo=0.45) comfort zone. In each case the metabolic rate was 1.1. The diamond symbol represents the zone temperature set point employed by CERL (72°F).

The 72°F zone setpoint remains fixed for summer and winter periods of operation therefore likely results in periods of discomfort (irrespective of the operating mode 0, 1, or 2) during the warmer (summer) periods. This is evidenced by the setpoint residing well left of the summer comfort zone (black-colored lines).

Table 25 shows the percent of the total amount of time each zone was in the comfort zone. In all modes the zone temperature and humidity are in comfort zone only about 10% of the time with mode 1 having the best comfort but at such a small margin compared to the other modes that the difference is essentially negligible. In actuality the occupants 'likely' adapt and dress more warmly suggesting a 'clo' factor larger than the 0.45 used to create the summer comfort zone. To account for this the 'clo' value was increased by +0.5 to create a new comfort zone as shown in the chart in Figure 29.

Table 26 uses the updated comfort zone and shows the percent of the total amount of time each zone was in the comfort zone. In all modes, zone temperature and humidity are within the comfort zone nearly 100% of the time with only a slight decrease in thermal comfort in modes 1 and 2 as compared to the mode 0.

Table 27 provides an indication of how well each zone's temperature setpoint is maintained in each mode. The calculation methodology consisted of the absolute value of the difference between zone temperature and setpoint at each 15 minute interval over the (roughly 1 year) duration of the test and then all of these values were averaged. The results show that modes 1 and 2 do not average significantly further from setpoint than mode 0.

Figure 28. Representative Zone Thermal Comfort for CERL AHU-1 Zone 2

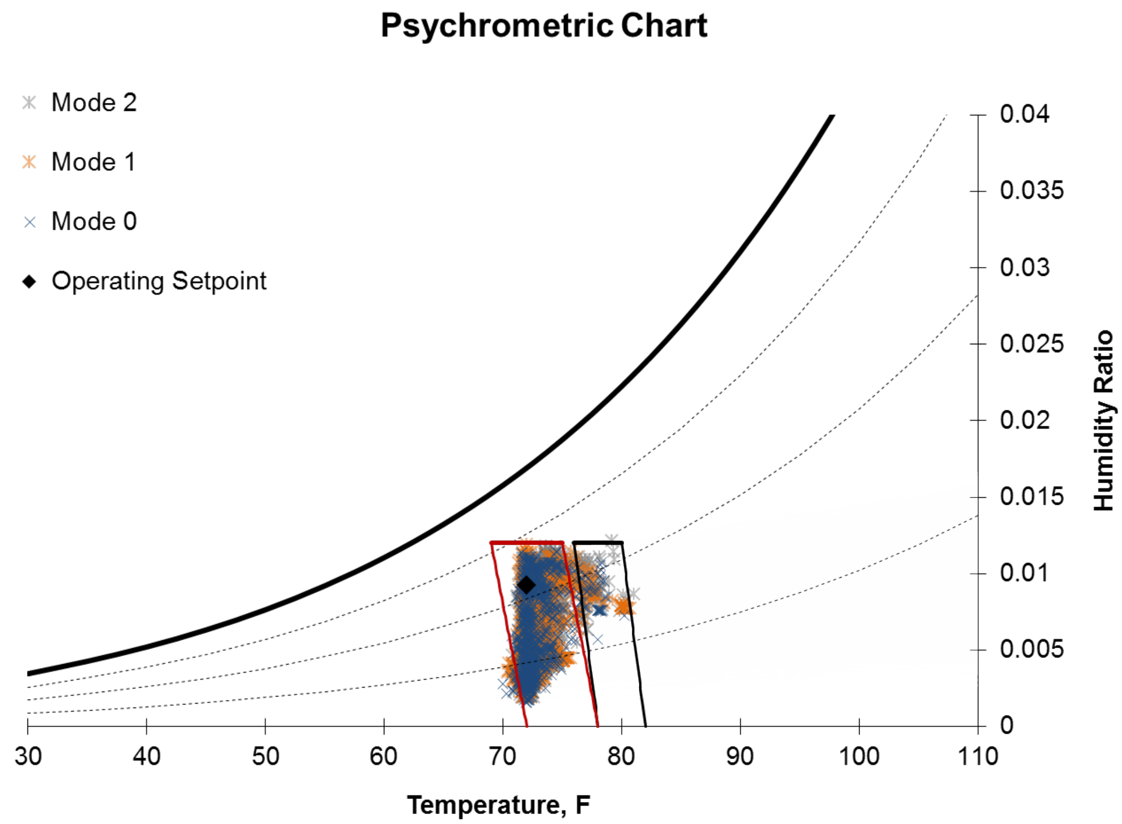


Table 25. Time Spent Within The Comfort Zone For Each AHU, Zone And Mode For CERL

	AHU 1			AHU 2		
	Mode 0	Mode 1	Mode 2	Mode 0	Mode 1	Mode 2
Zone 1	10.2%	13.1%	8.4%	9.8%	10.7%	8.3%
Zone 2	12.7%	13.6%	12.7%	12.8%	13.2%	10.9%
Zone 3	9.2%	10.5%	9.2%	5.2%	7.4%	5.3%
Zone 4	3.5%	3.5%	2.1%			
Zone 5	0.6%	1.0%	1.2%			
Total	7.2%	8.3%	6.7%	9.3%	10.4%	8.2%
Delta from Mode 0		1.1%	-0.5%		1.2%	-1.1%

Note: Systems have different numbers of zones. Empty entries indicate that zone does not exist.

Figure 29. Adjusted Zone Thermal Comfort for CERL AHU-1 Zone 2

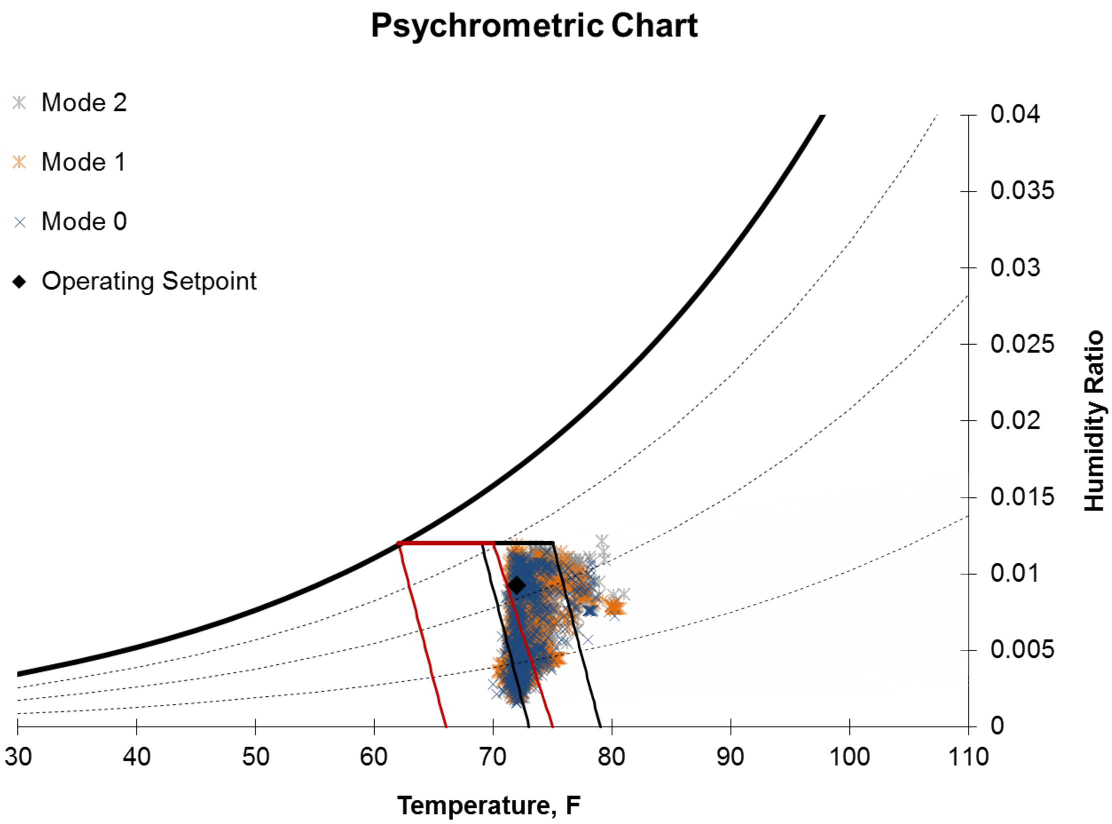


Table 26. Time Spent Within The Comfort Zone For Each AHU, Zone And Mode For CERL

	AHU 1			AHU 2		
	Mode 0	Mode 1	Mode 2	Mode 0	Mode 1	Mode 2
Zone 1	97.8%	97.2%	98.3%	96.7%	96.0%	98.9%
Zone 2	95.2%	95.1%	95.9%	95.6%	94.3%	97.5%
Zone 3	96.1%	95.7%	97.1%	100.0%	98.1%	100.0%
Zone 4	95.6%	92.0%	93.6%			
Zone 5	94.8%	93.4%	94.3%			
Total	95.9%	94.7%	95.8%	97.4%	96.1%	98.8%
Delta from Mode 0		-1.2%	-0.1%		-1.3%	1.4%

Note: Systems have different numbers of zones. Empty entries indicate that zone does not exist.

Table 27. Difference (ºF) Between Actual Zone Temperature And Set Point For CERL AHUs

	AHU 1			AHU 2		
	Mode 0	Mode 1	Mode 2	Mode 0	Mode 1	Mode 2
Zone 1	0.41	0.66	0.64	0.73	0.70	0.67
Zone 2	0.95	1.03	0.95	1.01	1.14	1.56
Zone 3	0.74	0.89	0.80	0.44	0.44	0.46
Zone 4	1.64	1.70	1.62			
Zone 5	2.58	2.69	2.69			
Total	0.70	0.86	0.79	0.73	0.76	0.90
Delta from Mode 0		0.16	0.09		0.03	0.17

Note: Systems have different numbers of zones. Empty entries indicate that zone does not exist.

7.0 COST ASSESSMENT

The complete renovation of a non-DDC controlled constant volume multizone air handler to a DDC-controlled variable volume air handler will require the installation of the following components:

- Premium efficiency supply fan motor
- Variable frequency drive(s) (VFD)
- Outdoor airflow measurement station (AFMS)
- CO2 or occupancy sensors
- Direct Digital Control (DDC) controls upgrade

It is not expected, however, that the conversion from constant to variable volume will generally provide the impetuous, or the justification, for this renovation. Rather it is likely that the conversion to variable volume will be an "add on" when the system is converted from non-DDC to DDC controls, or when the existing DDC controls are replaced. Therefore, all costs associated with the DDC upgrade are assumed to have been incurred, i.e., they are sunk costs, and the marginal financial burden of implementing the constant to variable volume retrofit will be limited to the following components:

- Variable frequency drive(s) (VFD)
- Outdoor airflow measurement station (AFMS)

Along with these components, and the labor costs necessary to install them, the retrofit will require a UMCS programmer to update the air handler sequence of operations to allow the following functionality:

- Fan speed reduction until zone dampers are near fully open
- Outside airflow requirements are met as fan speed changes
- Heating and cooling valves are closed automatically when not needed

- Demand controlled ventilation (based on CO_2 or occupancy sensors). This was implemented only in Mode 2, and not at all for Fort Bragg AHU 2.
- After-hours (unoccupied mode) temperature setback / shutdown

The cost benefit of this retrofit comes from the reduction in energy use and associated costs from reducing both fan output and simultaneous heating and cooling. Although there can be a significant implementation cost associated with this retrofit, it is much more cost-effective than a full system replacement (see Table 36). The implementation costs are kept low because this retrofit technique focuses almost entirely on instrumentation and controls rather than demolition and installation of ductwork and terminal units. This approach also leads to limited system down time and little disturbance to building occupants. In fact, no ductwork should be affected except at the location where instrumentation or equipment might be installed.

7.1 COST MODEL

The elements of the cost model are described in paragraphs 7.1.1 through 7.1.6. The actual values used in cost analysis are shown in the tables in paragraph 7.1.7.

7.1.1 Hardware Capital Costs:

Hardware capital costs are based on a multizone air handler with existing DDC retrofit components. In order to convert a constant volume multizone system to variable volume, multizone a single airflow monitoring station and a variable frequency drive for each fan serving the air handler must be installed to aallow the AHU to reduce fan speed while maintaining the necessary quantity of ventilation air. Detailed information on component costs was taken from Mechanical Costs with RSMeans Data published by Gordian.

7.1.2 Installation Costs:

Equipment installation and programming costs are all dependent on labor costs at the installation, and detailed information on installation labor costs was taken from Mechanical Costs with RSMeans Data published by Gordian. Programming labor was estimated using the billable rate for CERL's UMCS contractor.

Should multiple retrofits of similar systems be performed at the same site, economy of scale may be expected to reduce costs due to the repetition of programmer implementation and the ability to use management funds over multiple projects. Labor costs vary across the country and will require local estimates in establishing costs for potential retrofits.

7.1.3 Energy Costs:

Energy costs for each air handler are broken into 3 modes representing the normalized annual energy costs if the AHU had not been retrofitted (Mode 0), if the AHU had been retrofitted and the outdoor air flow was fixed (Mode 1), and if the AHU had been retrofitted and the outdoor air flow was controlled based on occupancy sensors (Mode 2). Section 6.0 described the data analysis to determine energy savings.

These costs embody all of the savings from the AHU retrofit. The utility rates used in this analysis were blended, meaning that the total annual utility bill costs (energy rates, demand charges, transmission charges, utility rebates, etc.) were divided by the total annual energy consumption. This cost method does

not take into account how utility energy rates, demand charges, fixed costs, and rebates all differ from one another. This lack of resolution into individual utility rate line items may have a very small impact on cost savings estimates, but this is considered negligible.

In order to understand the economics of the retrofit across the wide variety of utility rates across the county the payback period will be calculated using the actual utility rates at CERL and Fort Bragg, the highest and lowest non-residential electricity rates by state in the continental United States, and the highest and lowest natural gas rates by state in the continental United States published by the Energy Intelligence Agency for March 2017 (see Table 28).[5,6]

Table 28. Utility Prices For Economic Analysis

Commodity	CERL	Fort Bragg	High (state avg)	Low (state avg)
Electricity ($/kWh)	0.0636	0.0733	0.1603 (CT)	0.0454 (WA)
Natural Gas ($/therm)	0.84	0.62	1.91 (FL)	0.62 (ND)

7.1.4 Operator Training Costs:

AHUs are subject to changes in operation under a wide array of circumstances including when building operation schedules change or equipment must be replaced. Since the new UMCS sequences of operation implemented during the retrofit will be new to the building's mechanical crew, it makes sense to train them as to how to make operational changes to the new system.

Hourly rates are based on the billable rate for CERL's UMCS contractor. It is assumed that a full 8-hour day will be devoted to training the building's maintenance staff to operate the new system. These costs may only need to be incurred once if the upgraded systems are all similar and the same maintenance staff is in charge of each AHU that is upgraded, and thus multiple retrofits at the same installation may see a reduction in training costs per system.

7.1.5 Maintenance Costs:

The conversion to variable volume does not impact typical maintenance procedures for the AHU.

7.1.6 Hardware Lifetime:

The Energy Conservation Investment Program (ECIP) estimates that "EMCS or HVAC Controls" will have a 15 year lifespan, which is what was used for the total life of the project.

7.1.7 Cost Model Values

Table 29 and Table 30 show the RSMeans-based values used as the cost model for the air handler retrofits at CERL and Fort Bragg.

[5] "U.S. Energy Information Administration." EIA - Electricity Data. N.p., 23 June 2017. Web.
[6] "U.S. Energy Information Administration." *United States - Rankings - Natural Gas*. N.p., n.d. Web. 26 June 2017.

Table 29. RSMeans-Based Cost Model For Multizone Air Handler Retrofit For CERL

		Estimated Costs	
Cost Element	**Data Tracked During the Demonstration**	**AHU-1**	**AHU-2**
Hardware capital costs	Component Costs for Renovation	AFMS: $1,462 3 hp RAF VFD: $1,272 5 hp SAF VFD: $1,447	AFMS: $1,462 3 hp SAF VFD: $1,272
Installation costs	Labor costs for Renovation	AFMS: $243 3 hp RAF VFD: $733 5 hp SAF VFD: $733 8 Programming Labor Hours: $940	AFMS: $243 3 hp SAF VFD: $733 8 Programming Labor Hours: $940
Energy Costs	Energy costs (first year)	Mode 0: $5,104 Mode 1: $3,728 Mode 2: $3,143	Mode 0: $8,269 Mode 1: $3,347 Mode 2: $3,019
Additional Commissioning & Operator Training Costs	Training costs for new system	4 Commissioning Labor Hours: $470 4 Training Labor Hours: $470	4 Commissioning Labor Hours: $470 4 Training Labor Hours: $470
Maintenance Costs	Frequency of required maintenance Labor and material per maintenance action	Negligible	Negligible
Hardware lifetime	Replacement time based on field experience	Greater than Expected Project Lifespan	Greater than Expected Project Lifespan
Misc Costs	RSMeans Overhead, Profit, Bond, and Contingency Costs	Inflation: $975 Subcontractor OH: $875 Subcontractor Profit: $656 Subcontractor Bond: $219 Prime OH: $1,049.48 Prime Profit: $524.74 Prime Bond: $262 Contingency: $617	Inflation: $702 Subcontractor OH: $629 Subcontractor Profit: $472 Subcontractor Bond: $157 Prime OH: $755.02 Prime Profit: $377.51 Prime Bond: $189 Contingency: $444

Table 30. RSMeans-Based Cost Model For Multizone Air Handler Retrofit For Ft Bragg

		Estimated Costs		
Cost Element	**Data Tracked During the Demonstration**	**AHU-1**	**AHU-2**	**AHU-3**
Hardware capital costs	Component Costs for Renovation	AFMS: $1,468 3 hp SAF VFD: $1,278	AFMS: $1,468 3 hp SAF VFD: $1,278	AFMS: $1,468 3 hp SAF VFD: $1,278
Installation costs	Labor costs for Renovation	AFMS: $134 3 hp SAF VFD: $406 8 Programming Labor Hours: $520	AFMS: $134 3 hp SAF VFD: $406 8 Programming Labor Hours: $520	AFMS: $134 3 hp SAF VFD: $406 8 Programming Labor Hours: $520
Energy Costs	Energy costs (first year)	Mode 0: $1,084 Mode 1: $415 Mode 2: $374	Mode 0: $1,050 Mode 1: $644 Mode 2: $652	Mode 0: $1,131 Mode 1: $569 Mode 2: $578
Additional Commissioning & Operator Training Costs	Training costs for new system	4 Commissioning Labor Hours: $260 4 Training Labor Hours: $260	4 Commissioning Labor Hours: $260 4 Training Labor Hours: $260	4 Commissioning Labor Hours: $260 4 Training Labor Hours: $260
Maintenance Costs	Frequency of required maintenance Labor and material per maintenance action	Negligible	Negligible	Negligible
Hardware lifetime	Replacement time based on field experience	Greater than Expected Project Lifespan	Greater than Expected Project Lifespan	Greater than Expected Project Lifespan
Misc Costs	RSMeans Overhead, Profit, Bond, and Contingency Costs	Inflation: $543 Subcontractor OH: $487 Subcontractor Profit: $365 Subcontractor Bond: $122 Prime OH: $584.24 Prime Profit: $292.12 Prime Bond: $146 Contingency: $343.24	Inflation: $543 Subcontractor OH: $487 Subcontractor Profit: $365 Subcontractor Bond: $122 Prime OH: $584.24 Prime Profit: $292.12 Prime Bond: $146 Contingency: $343.24	Inflation: $543 Subcontractor OH: $487 Subcontractor Profit: $365 Subcontractor Bond: $122 Prime OH: $584.24 Prime Profit: $292.12 Prime Bond: $146 Contingency: $343.24

7.2 COST DRIVERS

7.2.1 Existing Components:

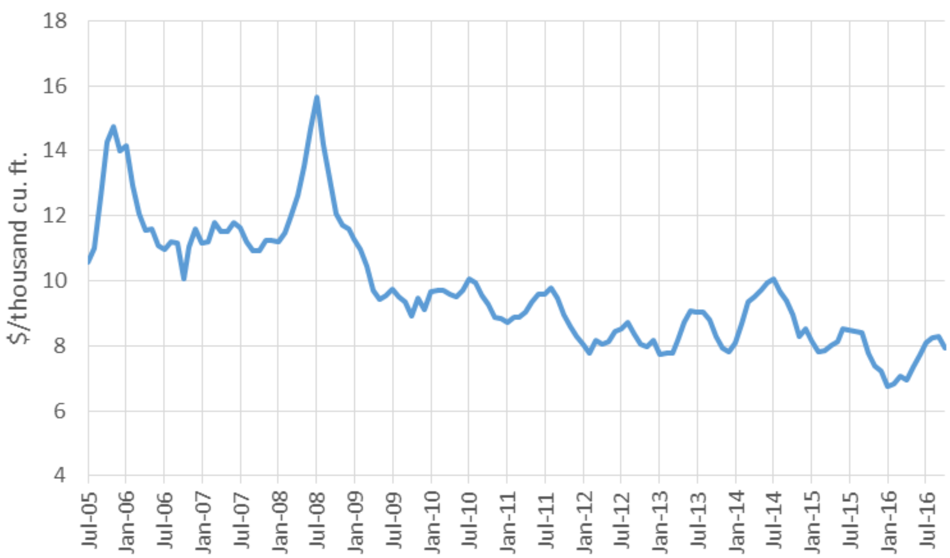
Many multizone AHUs will have undergone incremental improvements over the years. If these improvements involve installation of any of the components necessary for upgrade, then the cost of the upgrade will be reduced.

7.2.2 Energy Costs:

Electricity costs per kilowatt hour were 13% higher for Ft Bragg than for CERL and natural gas costs per therm were 26% higher for CERL than for Ft Bragg. The higher the energy costs, the faster the AHU retrofit investment will pay for itself. Assuming similar energy savings, multizone to VAV retrofits will be more cost-effective in regions with higher energy costs.

Energy costs also change over time. Do in part to the rapid increase in domestic oil and natural gas production energy costs have dropped significantly in the United States (see Figure 30). Similar market shifts are a risk to the return on investment of energy conservation projects. In order to mitigate risk due to market uncertainty the Department of Energy (DOE) published projected annual energy cost escalation rates for each state in the United States through 2043 by different market sectors (residential, commercial, and industrial).

Figure 30. Energy Information Agency Natural Gas Price Data



7.2.3 AHU Size And Regional Heating And Cooling Loads:

Once project costs and energy unit costs are determined the last component to identifying the cost-effectiveness of a multizone to VAV retrofit is the amount of energy that will be conserved. The region of the United States that the AHU is functioning in will make a large difference on the amount of energy it will consume in order to meet heating and cooling loads. CERL is located in Illinois and Ft Bragg is located in North Carolina. Both of these locations are in the ASHRAE moist climate zones. Of the 7 ASHRAE temperature zones represented in the continental United States Ft Bragg is in Zone 3 and CERL is in zone 5. Therefore, this study represents only a subset of the possible savings opportunity. In general, more extreme climates are expected to see higher annual energy savings and more mild climates are expected to see lower annual energy savings from an AHU retrofit.

7.3 COST ANALYSIS AND COMPARISON

7.3.1 Basic Site Descriptions:

CERL is located in Champaign, Illinois, and consists of three buildings interconnected by two hallways. AHU-1 and AHU-2 are located in Building 2, in above Room 2014 and in Mechanical Room 2127 respectively. The buildings primarily house laboratories and offices. The site has an existing UMCS which was used for data collection on site.

Fort Bragg is a Forces Command installation located in Cumberland and Hoke Counties, North Carolina. Due to its age it has numerous existing HVAC systems including multizone systems. Fort Bragg consists of approximately 161,000 acres. Fort Bragg's facilities include 2,176 structures (with approximately 1200 considered 'major') and 25.2 million sq. ft. total buildings. The site has an existing UMCS which was used for data collection on site.

7.3.2 Life Cycle Cost Development Approach

Life cycle costs were calculated using the Building Life Cycle Cost Program version 5.3-16 (BLCC5) developed by the National Institute of Standards and Technology (NIST). Of the array of analysis modules available in BLCC5, the FEMP Analysis module was used in accordance with ESTCP standards. 5 models were created, one for each retrofitted AHU. Within each model 3 alternatives were created to represent life cycle costs for Mode 0 (Base Case), Mode 1, and Mode 2.

7.3.3 Assumptions For Life Cycle Cost Analysis

To account for the time value of money, a real discount rate of 3.0% was selected from the Office of Management and Budget's "Life-Cycle Costing Manual for the Federal Energy Management Program (FEMP)." It was assumed that the time to complete the upgrade was negligible compared to the length of the study period, so the service date was 0 months after the base date. In accordance with ECIP guidelines, the assumed service period of the retrofit was 15 years.

Due to limited insight into energy tariffs, blended electricity and natural gas rates were used in the analysis. Energy escalation rates were based off DOE projected annual escalation rates for commercial utilities in the state where each AHU resides. The capital costs for Modes 1 and 2 are estimated based on RSMeans Mechanical Data.

7.3.4 Results for Incremental Retrofit

Regardless of the significant energy consumption reductions seen across all air handlers and operating modes (see Table 31) not all of the air handler retrofit projects successfully reduced life cycle costs over the study period of 15 years. The success of the retrofit at CERL is largely due to the relatively high baseline energy consumption of the CERL AHUs, making them good economic candidates for the retrofit. Even though Ft Bragg AHUs 2 and 3 were able to reduce energy costs by 38% and 49%, respectively, due to their relatively low baseline energy consumption the AHUs still failed to pay back in a 15-year lifespan. For this reason, the AHU retrofit is suggested only for units with similar, or higher, energy consumption than the CERL AHUs.

Table 31. Reduction in Life Cycle Energy Costs For Incremental Retrofits

Life Cycle Costs	CERL AHU-1	CERL AHU-2	Ft Bragg AHU-1	Ft Bragg AHU-2	Ft Bragg AHU-3
Mode 0 (Base Case)	$60,919	$98,702	$13,693	$13,176	$14,347
Mode 1 (Percent Reduction)	$57,403 (27%)	$49,250 (60%)	$12,574 (61%)	**$15,358** (38%)	**$14,515** (49%)
Mode 2 (Percent Reduction)	$50,415 (38%)	$45,340 (63%)	$11,994 (65%)	**$15,480** (37%)	**$14,633** (48%)

Although the sample size is small, there does not appear to be a strong correlation between air handler size (baseline energy consumption) and energy savings potential (see Figure 31). Because retrofit costs do not increase linearly with AHU size, it is expected that large AHUs with high space conditioning loads will have faster payback periods, and higher savings-to-investment ratios, than smaller AHUs with lower space conditioning loads (see Table 32).

Figure 31. AHU Size versus Energy Savings

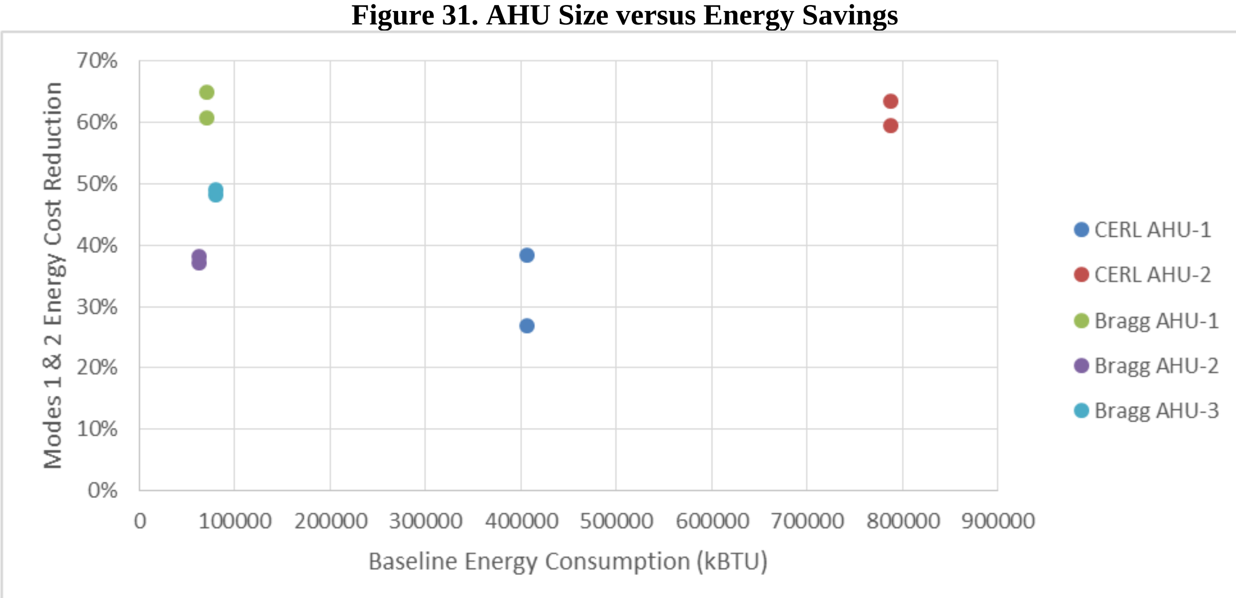


Table 32. Simple Payback and Savings-to-Investment Ratios For Incremental Retrofit

Life Cycle Costs	CERL AHU-1	CERL AHU-2	Ft Bragg AHU-1	Ft Bragg AHU-2	Ft Bragg AHU-3
Mode 1	Payback: 10 yrs SIR: 1.27	Payback: 3 yrs SIR: 6.32	Payback: 11 yrs SIR: 1.16	Payback: N/A SIR: 0.70	Payback: 13 SIR: 0.98
Mode 2	Payback: 7 yrs SIR: 1.81	Payback: 3 yrs SIR: 6.74	Payback: 10 yrs SIR: 1.24	Payback: N/A SIR: 0.68	Payback: 13 SIR: 0.96

Since regional variations in utility rates are expected to have a large impact on the retrofit payback period, Table 33 and Table 34 present expected payback periods based on actual utility rates (in this case, the average of CERL and Fort Bragg rates) and the highest and lowest state-wide utility rates in the continental United States (see Table 28) for several energy savings scenarios that represent the range of savings seen in Table 31. Table 33 values are based on a hypothetical 3 HP AHU that has an upgrade

cost of $7,725, a baseline electricity consumption of 10,864 kWh, and a baseline natural gas consumption of 2,133 therms. These values for the hypothetical 3 HP AHU were derived from averaging the 4, 3 HP AHUs that were included in the study. Table 34 values are based on the only 8 HP AHU in the study (CERL AHU-1).

Table 33. 3 HP AHU Simple Payback Matrix

	30% Savings	40% Savings	50% Savings	60% Savings
US High	5 yrs	4 yrs	3 yrs	3 yrs
Actual	11 yrs	8 yrs	7 yrs	6 yrs
US Low	13 yrs	10 yrs	8 yrs	7 yrs

Table 34. 8 HP AHU Simple Payback Matrix

	30% Savings	40% Savings	50% Savings	60% Savings
US High	4 yrs	3 yrs	3 yrs	2 yrs
Actual	10 yrs	8 yrs	6 yrs	5 yrs
US Low	12 yrs	10 yrs	8 yrs	7 yrs

7.3.5 Costs For Complete DDC Retrofit

As is evident from the analysis presented for the incremental retrofit, and given that a full retrofit will cost significantly more than the incremental, it’s clear that most of these systems will not have payback less than 15 years for the full retrofit. Due to its large baseline energy consumption CERL AHU-2, may achieve a reasonable savings (and payback) for the full retrofit costs, and was further analyzed. Since this system was fully renovated as part of this demonstration, actual installation costs were available. The costs for demonstration-specific monitoring components were removed and the life cycle cost and payback were analyzed based on the actual installation costs for a full retrofit. These costs should be considered conservative compared to RSMeans or expected costs for other projects as they include additional contactor time and risk due to the nature of a demonstration project.

Table 35. 15-Year Life Cycle Costs For Complete DDC Retrofit for CERL AHU-2

Life Cycle Costs	Life Cycle Costs	SIR	Simple Payback
Base Case (Mode 0)	$98,702	n/a	n/a
Mode 1	$88,189	1.22	11 years
Mode 2	$84,279	1.30	10 years

7.3.6 Comparison To Renovation To Variable Air Volume (VAV) System (With VAV Boxes)

The cost section has, until this point, been focused on the merits of upgrading a multizone air handler to function with variablevolume capability in comparison to only upgrading DDC controls and leaving the unit to operate as a constant volume multizone air handler. Another potential scenario is to compare the upgrade of a multizone unit to function with variable volume capability versus doing a full replacement of the multizone unit with a variable air volume (VAV) system incorporating VAV terminal units with reheat . Although a full economic analysis on this scenario is out of the scope of this project, Table 36 summarizes estimates from a local contractor to renovate the two systems at CERL and gives an indication of the large amount of money that can be saved when converting a constant volume multizone to variable volume instead of a full system replacement.

Table 36. Replacement/Retrofit Cost Comparison

CERL Initial Upgrade Costs			
System Replacement		System Retrofit	
CERL Executive Office VAV (2014)	CERL Room 2120 VAV (2015)	CERL AHU-1 MZ to VAV retrofit (2015)	CERL AHU-2 MZ to VAV retrofit (2015)
$535,000	$750,000	$20,500	$48,239

8.0 IMPLEMENTATION ISSUES

In order to identify the applicability and interest in constant to variable volume multizoneretrofits in the DoD a questionnaire was sent to many CONUS installations. After accounting for duplicated responses, there were 78 individual respondents representing more than 39,000 BBTU of installation energy consumption and between 14,816 and 26,475 individual multizone air handlers. The majority of installations (25 of 48) that indicated their level of interest in the constant volume to variable volume retrofit responded with “very interested”. This represents a large potential for cost and energy savings if large and energy-intensive multizone air handlers are targeted for retrofit.

Table 37. Questionnaire Summary

	Army	Air Force	Navy
# of Responses	47	27	4
Annual Energy Consumption (BBTU)	21102	15452	2470
# of Buildings with HVAC	10,252 – 16,350	4,529 – 9,325	353 – 800
# of MZ AHUs	2,597 – 3,266	1,293 – 1,665	26 – 35
Level of Interest in MZ-to-VAV Retrofit	Very Interested: 16 Moderately Interested: 4 Somewhat Interested: 6 Not Interested: 3	Very Interested: 7 Moderately Interested: 3 Somewhat Interested: 4 Not Interested: 2	Very Interested: 2 Moderately Interested: 1 Somewhat Interested: 0 Not Interested: 0

8.1 FAN SPEED CONTROL – SEQUENCE OF OPERATION LOGIC

Reduction in AHU fan speed is one of the biggest benefits of this technique. The sequence of operation is a bit complex and should be checked to verify that the control logic programmed into the digital controller performs properly. A performance verification test (PVT) used for the demonstration project is in the appendix.

8.2 FAN SPEED CONTROL – ZONE DAMPER COMMAND

Reduction in AHU fan speed is one of the biggest benefits of this technique. Zone damper command has a significant impact on fan speed as it is used to set the AHU fan speed. Things that can negatively impact damper command include:

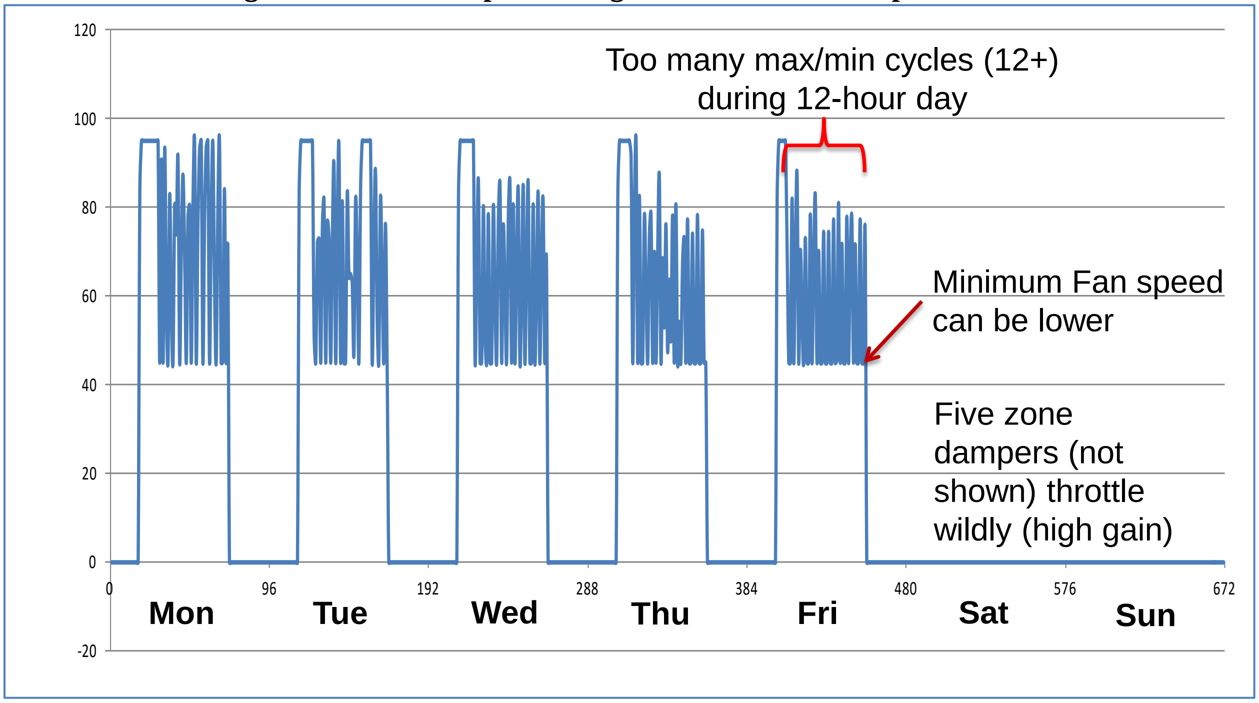
-Zone damper PID tuning constants
-Zone heating or cooling load imbalance
-Zone controller or sensor malfunction

Fan speed performance should be checked during commissioning, perhaps through a 1-week long endurance test where fan speed and damper commands are logged and then inspected.

8.2.1 Zone Damper PID Tuning Constants

In its pre-commissioned state, the figure below shows how AHU-2-001 supply fan was cycling fairly frequently on a daily basis (see Figure 32). Inspection revealed that the individual zone dampers were cycling due to an aggressive integral gain setting, resulting in the fan cycling. The aggressive integral gain setting was present in the system pre-retrofit system therefore were a product of prior commissioning (or lack thereof). This suggests zone damper PID control 'tuning' is important. The figure also shows that the minimum fan speed was initially set too high in the system pre-retrofit state.

Figure 32. Zone Damper Tuning and Minimum Fan Speed Issues



8.2.2 Zone Heating Or Cooling Load Imbalance

If the heating or cooling load in one or more zones is rarely or never met this can impact performance. The byproduct is that the temperature setpoint is not met and the thermostat/controls will always or frequently be commanding the zone damper to full open to heating or cooling. This will cause the AHU fan to run at full speed most if not all of the time. This project considered this possibility and Section 6 showed this was not a problem in the demonstration systems, but it should be considered a distinct possibility.

8.2.3 Zone Controller Or Sensor Malfunction

Similar to heating or cooling load imbalance, a malfunctioning controller can also command the zone damper to full open to heating or cooling.

9.0 REFERENCES

ANSI/ASHRAE Standard 55-2010. Thermal Environmental Conditions for Human Occupancy.

Whole Building Design Guide (WBDG) web site: http://www.wbdg.org/

Unified Facilities Guide Specification (UFGS) 23 09 23. ‘LonWorks Direct Digital Control for HVAC and Other Building Control Systems’

Unified Facilities Guide Specification (UFGS) 25 10 10. 'LonWorks Utility Monitoring and Control System (UMCS)'

APPENDIX A POINTS OF CONTACT

Point of Contact	Organization	Phone & E-mail	Role in Project
Joe Bush	U.S. Army Corps of Engineers ERDC-CERL	217-373-4433 joseph.bush@usace.army.mil	Team Member
Brian Clark	“	brian.c.clark@usace.army.mil	Team Member
Sean Wallace	“	sean.m.wallace@usace.army.mil	Team Member
Dino Mitsingas	“	-	Team Member

APPENDIX B ACRONYMS

ASHRAE	American Society of Heating, refrigerating, & air-conditioning engineers
AHU	Air handling unit
BAS	Building Automation System
BTU	British thermal unit
CERL	Construction Engineering Research Laboratory
CFM	cubic feet per minute
CAV	Constant air volume
CV	Constant volume
ECB	Engineering Construction Bulletin
ERDC	Engineer Research Development Center
ESTCP	Environmental Security Technology Certification Program
HQIMCOM	Headquarters Installation Management Command
HQUSACE	Headquarters U.S. Army Corps of Engineers
HVAC	Heating, ventilating, and air-conditioning
Msf	Million square feet
MZ	Multizone
OA	Outdoor air
sf	Square feet
UFC	Unified Facilities Criteria
UFGS	Unified Facilities Guide Specification
UMCS	Utility Monitoring and Control System
VAV	Variable air volume
VFD	Variable frequency drive
WBDG	Whole Building Design Guide

APPENDIX C PERFORMANCE VERIFICATION TEST (SAMPLE)

AHU [ ] Performance Verification Test (Sample)

Test #	Action Item	Expected Response	Recorded Value (where applicable)	Passed (Yes/No)	Verified By	Date	Notes
Test Procedures							
Graphics (M&C Configuration and System Displays)							
1	Start-Up and Start-Up Testing Report submitted and accepted	Start-Up and Start-Up Testing Report submitted and accepted					
2	Verify that all point shown as requiring M&C Display on the Points Schedule are included in the system display.	All points required by the Points Schedule are shown on the system graphics					
3	Verify that all point shown as requiring M&C Overrides are included on the system graphic as overide points.	All points required by the Points Schedule are overridable via the system graphics.					
4	Verify that up to 25% of overrides of the Govt choice actually override the indicated point, and that the override can be released from the graphics display.	All tested overrides function properly - the point can be overridden and then released.					
5	Verify that all alarms required by the Points Schedule are configured as indicated.	All alarms required by the Points Schedule are configured.					
6	Verfiy that all trends required by the Points Schedule are configured and values are being trended.	All trends required by the Points Schedule are configured and trending values.					
LDP Configuration							
7	Verify that all points shown on the Points Schedule as requiring LDP display or override are properly configured to display or provide override.	Display and overrides are provided in accordance with Points Schedule.					
Sensor Accuracy							
8	One point accuracy check for up to three sensors of each type of the government's choosing (except for BTU meter or AFMS).	Each sensor exhibits accuracy to the specified standard					
9	Command the HD and CD valves to closed	CD-T and HD-T should be about the same as MA-T, record these temperatures.					
10	Command the OA-D to full open	MA-T should be about the same as OA-T, record these temperatures.					
11	Command the OA-D to full closed	MA-T should be about the same as RA-T, record these temperatures.					
12	For each room with occ sensor, create motion outside doorway and monitor occupancy sensor. (Note: If occupancy sensor does not have visual indication of sensing motion the control system may be used to monitor the sensor. In this case the occupancy sensor timeout may be temporarily set to a lower value for this test, provided it is reset after the test)	Occ sensors does not ‘see’ beyond the doorway.					

13	For each room with occ sensor, create motion at remote points in the room. (Note: If occupancy sensor does not have visual indication of sensing motion the control system may be used to monitor the sensor. In this case the occupancy sensor timeout may be temporarily set to a lower value for this test, provided it is reset after the test)	Occ sensor senses motion throughout the entire room.					
14	For up to 3 occupancy sensors of the Government's choosing, visually verify the time-out settings at the sensor.	Verify settings are in accordance with the specifications.					
Supply Fan VFD Operation							
15	From the Supply Fan VFD, turn the H-O-A switch to Off	The VFD should ramp the fan speed down.					
		The VFD should stop the fan					
16	From the Supply Fan VFD, turn the H-O-A switch to Hand	The VFD will start the fan					
17	From the Supply Fan VFD, adjust the frequency reference to 50% (30Hz)	The VFD will drive the fan to the reference frequency					
18	From the Supply Fan VFD, adjust the frequency reference to 1%. Once fan speed reaches a minimum record minimum fan speed.	Fan speed ramps down to the configured minimum fan speed.					
18	From the Supply Fan VFD, turn the H-O-A switch to auto	The VFD will return to automatic control, and operate according to the fan capacity control loop.					
Fan Capacity/Mode Control *(These tests shall be run sequentially.)*							
19	From the OWS override the system into Unoccupied Mode.	SF will stop.					
		The chilled water valve will close to the coil.					
		The hot water valve will close to the coil.					
		The outside air dampers will close.					
		The exhaust air damper will close.					
		The return air damper will open 100%.					
20	From the OWS command the system to "basic mode" and override the system into Occupied Mode.	The System Display indicates that the system is operating in "Basic mode".					
		SF will start.					
		VFD shall ramp the supply fan to 100%.					
		The outside air damper will open to the (fixed) position. Record the damper command position.					
		The outdoor air flow displayed at the OWS system display equals the 'Basic Mode' outdoor airflow setpoint. Record the value of the measured outdoor airflow.					
		Hot Deck and Cold Deck are enabled (HW/CHW valves modulate as needed to maintain HD-T-SP and CD-T-SP).					
		Economizer functions according to the sequence of operation.					
21	With the system still in Basic Mode and Occupied,override each zone damper to 50%.	The fan speed does not change and runs continuously at 100% speed					
22	Place system into Advanced mode	System display indicates system is operating in Advanced Mode					
		Fan speed reduces					

23	When fan speed is about 60%, override one damper to 95%	Fan speed stabilizes					
24	Override same damper to 98%	Fan speed increases					
25	Allow fan speed to reach 100%, then override same damper to 20%	Fan speed reduces					
26	Override same damper to 5%	Fan speed stabilizes					
27	Override same damper to 2%	Fan speed increases					
28	Override all dampers to 80%	Cold deck is enabled, Hot deck is disabled					
29	Override points such that economizer runs when the ecnomizer logic is enabled.	Economizer runs					
30	Override one damper to 50%	Cold deck is enabled, Hot deck is disabled, economizer runs					
31	Override one damper to 20%	Cold deck is enabled, Hot deck is enabled, economizer runs					
32	Override all dampers to 20%	Cold deck is disabled, Hot deck is enabled, economizer doesn't run					
33	Override one damper to 50%	Cold deck is disabled, Hot deck is enabled, economizer doesn't run					
34	Override one damper to 80%	Cold deck is enabled, Hot deck is enabled, economizer runs					
35	Override all dampers to 80%	Cold deck is enabled, Hot deck is disabled, economizer runs					
36	Clear all overrides	Fan speed modulates to maintain most open/closed damper at 95%/5%. Economizer runs according to the enable logic and limits. Dampers modulate to maintain ZN-T-SP and decks are enabled or disabled as indicated by the sequence.					
38	Record fan speed PI values	Record fan speed PI values					
Occupancy Modes (make sure all deadbands are 5 Deg F or less for this test):							
39	From the OWS, override the time schedule for unoccuppied to be current time plus 2 minutes.	After 2 minutes the system goes to Unoccupied mode.					
		The supply fan should stop					
		Return Air Damper should open					
		Unit Outside Air Damper should close					
		Water valves close.					
40	From the OWS, adjust the night setback High-limit (HL) temperature setpoint to be the highest current space temperature minus 6 degree F.	Fan Capacity loop enables.					
		Econ loop enables					
		Cold Deck control loop is enabled					
		Zone temp control loop is enabled.					
41	From the OWS, adjust the night setback temperature setpoint to be the current space temperature plus 2 degF.	Fan Capacity loop is disabled. Unit returns to Unocc mode.					
		Econ loop is disabled. Unit in Unocc mode.					
		Cold Deck control loop is disabled. Unit in Unocc mode.					
		Hot Deck control loop does not enable.					
42	From the OWS, adjust the night setback Low-limit (LL) temperature setpoint to be the lowest current space temperature plus 6 deg F.	Fan Capacity loop enables.					
		Zone Temp loop enables.					
		Hot Deck control loop is enabled					
43	From the OWS, adjust the night setback temperature setpoint to be the current space temperature minus 2 degF.	Fan Capacity loop is disabled. Unit returns to Unocc mode.					
		Econ loop is disabled. Unit in Unocc mode.					
		Cold Deck control loop is disabled. Unit in Unocc mode.					
		Hot Deck control loop does not enable.					

44	Release overrides.	System will return to normal control.					
Zone Temperature Control							
45	From the OWS, Increase the space zone sensor setpoint to 3 degF above the current space temperature.	Hot deck damper modulates more open.					
		Cold deck damper modulates more closed.					
46	From the OWS, decrease the space zone sensor setpoint to 3 degF below the current space temperature.	Hot deck damper modulates more closed.					
		Cold deck damper modulates more open.					
47	Record zone damper PI values for each zone						
Economizer Control (Testing during Winter) Be careful..Do not Freeze Chilled water coil)							
48	From the OWS, override the Economizer Enable Setpoint to a temperature 5 degrees lower than the outside air temperature.	The Econ mode is enabled.					
		The outside air, and return dampers will modulate to maintain the cold deck setpoint.					
49	From the OWS, override the Economizer Enable Setpoint to a temperature 5 degrees higher than the outside air temperature.	The Econ mode is disabled.					
		The outside air and relief air dampers are controlled to Outside Air Flow Control loop.					
50	Release all Overrides.	System will return to normal operation.					
Mixed Air Low-Limit Temperature (MA-LL) Control, Economizer Mode Off							
51	From OWS, when the fan speed is not at maximum, initially override the mixed air temperature low limit setpoint (MA-T-LL) to the current mixed air temperature (MA-T) plus 2 degrees.	The OA Damper should modulate closed					
52	From the OWS, return the mixed air temperature low limit setpoint (MA-T-LL) to the default value	The OA Damper should modulate open					
Hot Deck Reset Control (Basic Mode)							
53	Override system such that HD-T-SP is reset to higher limit	HD-T-SP is at HD-T-SP-HL					
54	Override system such that HD-T-SP is reset to lower limit	HD-T-SP is at HD-T-SP-LL					
Safeties and Alarms							
57	With the System in automatic, turn the VFD on the supply fan to the off position.	The supply fan VFD will turn off.					
		A specific supply fan failure will generate at the OWS.					
58	Return the H-O-A switch back to the auto position.	The supply fan VFD will start.					
59	With the system in automatic, unwire the Low Limit Sensor.	The Hot Deck control control loop enables, and setpoint goes to 75degF.					
		Outside air dampers will close.					
		The Hot Deck HW valves modulates to maintain temperature					
		A coil low limit alarm will generate at the OWS.					
60	Press the reset button.	Alarm clears at OWS. System returns to last auto control mode.					
61	Simulate a duct detector unit shutdown by manually tripping the return duct detector	AHU fans and all control modes are disabled.					

62	With the system in alarm, turn the H-O-A switch for the VFD's to the hand position and back to auto.	The VFD's will remain off.					
63	Press the reset button and the manual switch to reset the duct detector.	The alarms will clear and the system will return to automatic.					
Trend Download Procedure							
64	Demonstrate data transfer procedure	Data will be transferred and saved in at most 10 minutes					
System Mode							
65	Override the test mode to select an alternate mode	System is overriden to selected test mode and remains in selected mode.					
66	Test system mode scheduling/determination by changing time on M&C Server and observing the system mode output through a midnight transition (day and time transition)	System mode changes per schedule					
Other							
67	At the Governments request demonstrate compliance with any contract requirement that was not demonstrated in a test defined above.	Contract requirement is met.					

APPENDIX D ENERGY SAVINGS TABLES

D-1 Energy Savings For The Processed Demonstration Data for CERL

Table D-1. CERL AHU-1 Total Fan and BTU Meter Energy Savings for the Processed Data Set

Temperature Bins (F)	Mode 0				Mode 1				Mode 2			
	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
10-15	47	-	1,922	2,081	24	-	517	598	41	-	2,110	2,250
15-20	60	-	2,582	2,786	24	-	250	331	52	-	2,145	2,322
20-25	106	-	4,282	4,645	74	-	2,620	2,873	93	-	932	1,248
25-30	340	42	12,741	13,942	309	-	10,544	11,598	267	-	3,472	4,385
30-35	730	244	17,390	20,126	604	33	15,304	17,398	494	16	11,540	13,241
35-40	762	105	25,717	28,423	679	19	20,655	22,989	460	154	10,972	12,695
40-45	639	64	17,375	19,620	486	60	15,042	16,759	241	77	7,990	8,890
45-50	896	-	24,647	27,704	573	-	16,331	18,287	446	-	12,459	13,982
50-55	1,127	361	21,905	26,114	799	90	14,317	17,132	568	299	10,384	12,623
55-60	1,159	3,702	13,812	21,471	881	2,413	10,653	16,072	793	3,070	11,866	17,642
60-65	1,070	12,050	13,551	29,254	655	10,797	7,798	20,829	627	8,169	7,209	17,516
65-70	1,253	35,758	6,545	46,581	681	24,651	5,760	32,733	658	27,184	2,233	31,664
70-75	1,413	48,872	3,848	57,541	1,024	46,729	1,961	52,183	965	41,589	2,011	46,893
75-80	1,345	58,232	1,245	64,068	1,071	49,046	839	53,541	1,017	48,956	687	53,112
80-85	1,262	68,836	331	73,473	1,009	51,985	268	55,698	900	56,616	185	59,871
85-90	1,113	67,616	149	71,566	994	51,355	-	54,748	1,009	68,803	153	72,400
90-95	686	48,008	-	50,349	648	43,018	-	45,230	682	51,350	-	53,678
95-100	63	4,086	-	4,302	60	4,103	-	4,309	63	6,816	-	7,032
Total	14,071	347,976	168,044	564,044	10,593	284,299	122,857	443,309	9,375	313,097	86,349	431,444
Reduction (relative to mode 0)					24.7%	18.3%	26.9%	21.4%	33.4%	10.0%	48.6%	23.5%

Table D-2. CERL AHU-2 Total Fan and BTU Meter Energy Savings for the Processed Data Set

Temperature Bins (F)	Mode 0				Mode 1				Mode 2			
	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
15-20	9.2	-	3,132	3,164	6	-	4,770	4,791	-	-	-	0
20-25	22.5	-	4,565	4,642	3	-	5,895	5,906	4	-	9,028	9,042
25-30	43.9	-	1,871	2,021	10	-	5,497	5,531	10	-	10,530	10,563
30-35	92.4	-	4,121	4,437	30	26	17,531	17,660	31	59	13,633	13,798
35-40	118.8	-	31,874	32,279	26	34	15,105	15,228	34	69	9,059	9,244
40-45	118.8	51	35,329	35,786	20	33	13,550	13,649	24	9	8,989	9,081
45-50	179.8	44	50,786	51,444	40	262	13,141	13,538	48	205	10,945	11,312
50-55	292.3	636	82,091	83,724	103	565	13,753	14,671	66	529	11,567	12,321
55-60	226.7	1,520	67,552	69,845	89	1,411	11,839	13,554	83	1,382	13,588	15,252
60-65	263.3	3,103	73,449	77,451	85	3,588	16,338	20,215	80	2,832	13,466	16,570
65-70	276.9	9,179	40,872	50,997	125	7,061	14,926	22,415	106	6,332	8,495	15,187
70-75	311.6	11,418	40,393	52,875	200	11,483	4,032	16,198	185	9,969	7,524	18,124
75-80	296.6	12,818	22,385	36,216	198	12,021	4,071	16,768	211	11,445	16,731	28,895
80-85	261.9	13,332	16,997	31,223	158	10,533	1,844	12,915	164	10,626	5,293	16,480
85-90	202.7	10,589	661	11,941	137	9,757	135	10,360	165	9,477	5,001	15,040
90-95	95.4	5,234	-	5,560	82	5,198	-	5,478	88	5,258	-	5,558
95-100	9.8	509	-	543	10	621	-	654	10	630	-	665
Total	2,823	68,434	476,079	554,146	1,322	62,594	142,426	209,530	1,308	58,821	143,847	207,132
Reduction (relative to mode 0)					53.2%	8.5%	70.1%	62.2%	53.7%	14.0%	69.8%	62.6%

D-2 Energy Savings For The Processed Demonstration Data – Fort Bragg

Table D-3. Fort Bragg AHU-1 Total Fan and BTU Meter Energy Savings for the Processed Data Set

Temperature Bins (F)	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10	0	0	0	0	0	0	0	0	0	0	0	0
10-15	0	0	0	0	0	0	0	0	0	0	0	0
15-20	5	0	120	136	1	0	138	141	0	18	6	24
20-25	12	0	241	281	1	0	182	183	0	0	51	52
25-30	51	0	776	950	3	0	782	793	2	0	462	470
30-35	60	2	657	864	3	23	523	558	2	6	437	452
35-40	27	0	301	395	1	14	177	194	2	8	220	234
40-45	125	38	600	1,065	7	72	867	962	5	50	462	528
45-50	70	188	143	572	4	99	276	388	3	27	169	206
50-55	186	722	482	1,840	9	226	252	508	7	234	234	493
55-60	161	1040	298	1,888	7	289	117	429	7	239	47	309
60-65	226	2271	59	3,099	9	659	47	737	13	726	17	789
65-70	206	3081	10	3,793	11	1320	10	1367	11	1367	42	1,447
70-75	200	3929	30	4,643	13	2606	30	2680	19	2662	34	2,760
75-80	245	6246	23	7,107	21	4596	60	4728	15	4908	36	4,997
80-85	128	3971	15	4,423	9	2555	18	2605	10	2491	19	2,545
85-90	83	2527	11	2,820	6	1899	13	1933	9	1968	15	2,015
90-95	17	624	3	686	1	420	3	425	1	477	3	482
95-100	1	49	0	53	0	25	0	25	0	25	1	26
Total	1,804	24,690	3,770	34,614	106	14,802	3,496	18,658	108	15,207	2,255	17,829
Reduction (relative to mode 0)					94.1%	40.0%	7.3%	46.1%	94.0%	38.4%	40.2%	48.5%

Table D-4. Fort Bragg AHU-2 Total Fan and BTU Meter Energy Savings for the Processed Data Set

Temperature Bins (F)	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10	0	0	0	0	0	0	0	0	0	0	0	0
10-15	0	0	0	0	0	0	0	0	0	0	0	0
15-20	0	0	0	0	0	0	71	71	0	19	17	36
20-25	0	0	0	0	0	0	73	73	0	0	174	174
25-30	0	0	0	0	10	0	393	429	5	0	232	247
30-35	30	0	103	206	4	0	160	173	7	0	139	164
35-40	13	0	70	113	4	16	22	51	2	2	74	84
40-45	73	183	339	771	23	71	280	430	24	38	335	454
45-50	62	259	170	640	13	126	164	334	18	70	140	271
50-55	182	928	617	2,166	72	376	451	1074	62	428	451	1,089
55-60	158	1306	246	2,093	73	758	340	1348	72	519	242	1,007
60-65	245	2743	111	3,688	104	1506	191	2053	114	1978	91	2,459
65-70	220	3277	34	4,061	86	2686	42	3020	88	2384	176	2,860
70-75	213	3860	93	4,679	86	3561	67	3921	80	3309	313	3,895
75-80	258	5412	88	6,381	122	5406	174	5997	118	5510	263	6,176
80-85	130	3221	49	3,714	64	2971	205	3395	61	2985	163	3,358
85-90	83	2050	30	2,363	37	2178	202	2506	41	2218	232	2,589
90-95	18	527	11	598	9	519	14	565	7	558	13	596
95-100	1	39	0	44	1	27	1	30	1	37	1	40
Total	1,686	23,806	1,960	31,517	709	20,202	2,849	25,469	701	20,055	3,056	25,502
Reduction (relative to mode 0)					58.0%	15.1%	-45.4%	19.2%	58.4%	15.8%	-55.9%	19.1%

Table D-5. Fort Bragg AHU-3 Total Fan and BTU Meter Energy Savings for the Processed Data Set

Temperature Bins (F)	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10	0	0	0	0	0	0	0	0	0	0	0	0
10-15	0	0	0	0	0	0	0	0	0	0	0	0
15-20	4	0	98	111	0	0	142	143	0	25	40	65
20-25	10	0	257	291	0	0	156	157	0	0	136	137
25-30	42	6	825	974	1	2	785	790	0	1	478	480
30-35	47	10	557	729	0	32	402	435	0	10	451	462
35-40	21	6	261	339	0	29	175	204	0	13	215	229
40-45	99	58	726	1,123	1	136	651	791	0	91	679	771
45-50	64	177	331	727	0	147	288	436	0	79	266	347
50-55	167	748	1291	2,608	7	388	506	918	4	378	603	995
55-60	145	1073	618	2,185	8	641	293	962	18	459	255	775
60-65	216	2936	182	3,857	20	1240	188	1498	29	1611	124	1,833
65-70	190	3747	43	4,439	17	2708	60	2825	26	2480	222	2,792
70-75	185	4560	114	5,305	19	4102	129	4294	25	3773	238	4,097
75-80	211	7123	153	7,996	33	6502	363	6977	39	6806	376	7,315
80-85	112	4461	80	4,924	16	3570	160	3786	21	3644	180	3,895
85-90	67	2670	54	2,954	9	2426	120	2577	12	2600	146	2,787
90-95	10	593	17	643	3	599	31	641	3	665	30	706
95-100	1	51	1	55	0	33	2	36	0	42	2	45
Total	1,592	28,219	5,608	39,258	136	22,556	4,450	27,471	179	22,678	4,443	27,730
Reduction (relative to mode 0)					91.4%	20.1%	20.6%	30.0%	88.8%	19.6%	20.8%	29.4%

D-3 Energy Savings For 2016 Weather-Normalized Data – CERL

Table D-6. CERL AHU-1 Total Fan and BTU Meter Energy Savings for the 2016 Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
10-15	20	92	0	3,805	4,119	47	0	1,023	1,184	81	0	4,176	4,452
15-20	24	111	0	4,825	5,205	44	0	468	619	97	0	4,008	4,339
20-25	45	209	0	8,432	9,147	146	0	5,159	5,658	182	0	1,835	2,457
25-30	64	300	37	11,245	12,304	272	0	9,306	10,235	236	0	3,064	3,869
30-35	174	803	269	19,128	22,137	664	36	16,833	19,137	543	17	12,693	14,565
35-40	173	824	113	27,813	30,740	734	20	22,339	24,863	497	166	11,867	13,730
40-45	179	846	85	23,012	25,985	643	79	19,922	22,196	319	102	10,582	11,774
45-50	196	920	0	25,330	28,471	589	0	16,784	18,793	459	0	12,804	14,370
50-55	215	1,009	323	19,604	23,371	715	81	12,813	15,332	509	268	9,293	11,297
55-60	229	1,070	3,415	12,742	19,808	812	2,226	9,828	14,827	731	2,832	10,947	16,276
60-65	189	885	9,965	11,206	24,191	541	8,929	6,448	17,224	518	6,755	5,961	14,485
65-70	199	930	26,524	4,855	34,552	505	18,285	4,272	24,280	488	20,164	1,657	23,487
70-75	227	1,049	36,300	2,858	42,739	760	34,708	1,457	38,760	717	30,890	1,494	34,830
75-80	207	957	41,431	886	45,583	762	34,896	597	38,094	723	34,831	489	37,789
80-85	225	1,029	56,126	270	59,908	823	42,387	218	45,414	734	46,163	151	48,817
85-90	277	1,263	76,703	170	81,184	1,128	58,257	0	62,106	1,144	78,049	174	82,130
90-95	131	596	41,742	0	43,777	564	37,404	0	39,327	593	44,648	0	46,672
95-100	23	102	6,579	0	6,926	97	6,606	0	6,937	102	10,975	0	11,322
Total	2,795	12,996	299,613	176,180	520,148	9,847	243,913	127,465	404,987	8,674	275,861	91,195	396,660
Reduction (relative to mode 0)						24.2%	18.6%	27.7%	22.1%	33.3%	7.9%	48.2%	23.7%

Table D-7. CERL AHU-2 Total Fan and BTU Meter Energy Savings for the 2016 Weather-Normalized Data Set

Temp-erature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
10-15	20	21	0	6,889	6,959	2	0	10,489	10,495	0	0	0	0
15-20	24	26	0	4,436	4,524	12	0	5,728	5,769	0	0	8,772	8,772
20-25	45	41	0	1,842	1,983	11	0	5,412	5,449	8	0	10,368	10,396
25-30	64	59	0	2,816	3,016	13	0	11,978	12,021	7	0	9,315	9,340
30-35	174	102	0	52,756	53,103	26	18	25,001	25,109	35	16	14,994	15,129
35-40	173	164	0	61,134	61,692	23	40	23,447	23,564	36	74	15,554	15,751
40-45	179	175	59	61,352	62,008	27	24	15,875	15,990	34	12	13,222	13,350
45-50	196	221	134	67,141	68,028	42	269	11,248	11,660	45	195	9,460	9,810
50-55	215	243	471	78,009	79,307	79	483	13,672	14,427	59	473	15,691	16,366
55-60	229	231	1,609	86,621	89,018	88	1,408	17,549	19,257	92	1,581	14,464	16,361
60-65	189	228	3,066	28,862	32,706	73	2,986	10,540	13,773	71	2,492	5,999	8,732
65-70	199	205	6,860	27,594	35,153	94	5,249	2,708	8,278	78	4,706	5,087	10,061
70-75	227	233	8,831	18,177	27,801	150	8,779	3,213	12,504	138	7,485	13,207	21,162
75-80	207	203	9,317	13,855	23,864	143	8,655	1,503	10,645	147	7,972	4,315	12,789
80-85	225	222	11,800	766	13,323	147	9,681	157	10,338	153	9,789	5,801	16,111
85-90	277	242	14,839	0	15,667	208	14,571	0	15,282	240	13,827	0	14,646
90-95	131	108	7,545	0	7,915	116	7,693	0	8,089	130	7,659	0	8,101
95-100	23	15	1,228	0	1,280	21	1,377	0	1,450	23	1,435	0	1,513
Total	2,795	2,736	65,760	512,248	587,346	1,274	61,231	158,519	224,099	1,296	57,716	146,248	208,389
Reduction (relative to mode 0)						53.4%	6.9%	69.1%	61.8%	52.6%	12.2%	71.4%	64.5%

D-4 Energy Savings For 2016 Weather-Normalized Data – Fort Bragg

Table D-8. Fort Bragg AHU-1 Total Fan and BTU Meter Energy Savings for the 2016 Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10		0	0	0	0	0	0	0	0	0	0	0	0
10-15		0	0	0	0	0	0	0	0	0	0	0	0
15-20	8	18	0	482	544	4	0	554	565	1	70	24	97
20-25	23	51	0	1041	1,214	2	0	786	793	1	0	220	225
25-30	104	236	0	3592	4,398	14	0	3623	3672	11	0	2137	2,176
30-35	111	266	10	2914	3,831	15	101	2321	2473	11	28	1939	2,003
35-40	187	425	7	4697	6,153	18	214	2751	3027	25	124	3437	3,645
40-45	233	543	166	2605	4,624	28	314	3765	4176	20	219	2006	2,291
45-50	220	467	1248	949	3,792	25	656	1833	2575	20	180	1118	1,367
50-55	288	601	2327	1555	5,932	28	729	813	1637	23	755	754	1,589
55-60	251	537	3464	993	6,289	23	962	390	1431	22	798	157	1,031
60-65	329	663	6673	173	9,107	27	1935	138	2166	40	2134	50	2,319
65-70	422	884	13238	41	16,297	47	5672	44	5875	48	5874	180	6,217
70-75	434	931	18246	139	21,561	61	12100	139	12447	87	12363	156	12,817
75-80	345	751	19120	71	21,753	65	14069	184	14474	47	15024	112	15,296
80-85	160	360	11170	43	12,441	26	7187	51	7326	29	7006	55	7,159
85-90	90	205	6239	27	6,964	15	4688	33	4774	23	4859	37	4,975
90-95	40	92	3334	16	3,665	4	2246	14	2274	4	2547	16	2,577
95-100	4	10	440	2	475	0	220	1	222	0	222	5	229
Total	3,250	7,039	85,683	19,342	129,043	403	51,093	17,438	69,906	413	52,203	12,404	66,015
Reduction (relative to mode 0)						94.3%	40.4%	9.8%	45.8%	94.1%	39.1%	35.9%	48.8%

Table D-9. Fort Bragg AHU-2 Total Fan and BTU Meter Energy Savings for the 2016 Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10		0	0	0	0	0	0	0	0	0	0	0	0
10-15		0	0	0	0	0	0	0	0	0	0	0	0
15-20	8	18	0	127	190	0	0	126	126	0	76	69	145
20-25	23	52	0	327	505	0	0	315	315	0	0	256	256
25-30	104	239	0	1347	2,164	46	0	1744	1902	19	0	997	1,063
30-35	111	268	0	915	1,830	34	0	1417	1532	65	0	1234	1,456
35-40	187	427	0	2371	3,827	131	548	749	1744	73	73	2531	2,853
40-45	233	521	1304	2415	5,496	167	503	1992	3064	170	273	2384	3,237
45-50	220	492	2055	1350	5,084	101	1001	1306	2654	144	557	1108	2,155
50-55	288	645	3286	2184	7,670	255	1332	1598	3802	218	1515	1597	3,857
55-60	251	559	4613	869	7,391	259	2678	1200	4761	255	1832	855	3,556
60-65	329	718	8061	325	10,838	307	4424	561	6031	336	5811	266	7,224
65-70	422	946	14079	144	17,450	368	11542	179	12976	379	10244	754	12,290
70-75	434	987	17927	433	21,728	400	16536	310	18210	371	15368	1455	18,088
75-80	345	791	16566	269	19,534	374	16548	532	18357	361	16866	806	18,905
80-85	160	366	9058	138	10,446	180	8357	577	9549	173	8397	458	9,444
85-90	90	204	5063	74	5,834	91	5379	498	6189	101	5476	572	6,394
90-95	40	94	2818	58	3,195	48	2774	77	3017	39	2982	70	3,186
95-100	4	12	347	3	391	6	239	9	267	6	331	9	359
Total	3,250	7,340	85,177	13,347	123,571	2,767	71,862	13,192	94,495	2,710	69,799	15,422	94,468
Reduction (relative to mode 0)						62.3%	15.6%	1.2%	23.5%	63.1%	18.1%	-15.5%	23.6%

Table D-10. Fort Bragg AHU-3 Total Fan and BTU Meter Energy Savings for the 2016 Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10		0	0	0	0	0	0	0	0	0	0	0	0
10-15		0	0	0	0	0	0	0	0	0	0	0	0
15-20	8	15	0	394	445	1	0	570	572	0	101	159	260
20-25	23	43	0	1112	1,257	1	0	677	680	1	0	588	591
25-30	104	194	27	3821	4,509	3	11	3638	3657	0	7	2214	2,222
30-35	111	210	45	2471	3,231	2	143	1782	1931	1	46	1999	2,048
35-40	187	325	98	4070	5,279	4	451	2721	3186	1	205	3356	3,564
40-45	233	432	252	3151	4,877	5	593	2825	3435	1	395	2949	3,348
45-50	220	425	1176	2195	4,820	3	975	1908	2894	2	527	1765	2,299
50-55	288	537	2411	4161	8,405	23	1252	1630	2960	14	1217	1943	3,207
55-60	251	482	3576	2059	7,281	28	2137	975	3206	59	1530	850	2,581
60-65	329	636	8626	536	11,332	60	3645	554	4402	85	4733	364	5,387
65-70	422	818	16102	183	19,075	72	11635	257	12138	114	10655	953	11,996
70-75	434	858	21176	530	24,636	86	19048	597	19939	116	17521	1108	19,026
75-80	345	646	21802	467	24,475	102	19901	1110	21358	119	20834	1152	22,392
80-85	160	316	12546	225	13,849	45	10042	451	10648	59	10248	507	10,956
85-90	90	166	6592	134	7,293	22	5990	296	6363	29	6420	362	6,881
90-95	40	51	3170	89	3,434	18	3200	164	3424	17	3555	163	3,775
95-100	4	9	456	5	493	4	291	20	323	3	371	20	400
Total	3,250	6,164	98,056	25,603	144,691	478	79,312	20,174	101,115	621	78,366	20,449	100,932
Reduction (relative to mode 0)						92.3%	19.1%	21.2%	30.1%	89.9%	20.1%	20.1%	30.2%

D-5 Energy Savings For Historical Weather-Normalized Data - CERL

Table D-11. CERL AHU-1 Total Fan and BTU Meter Energy Savings for the Historic Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
-10--5	4	19	0	1,029	1,093	11	0	544	581	12	0	634	675
-5-0	4	19	0	974	1,037	11	0	517	554	12	0	598	640
0-5	13	60	0	2,987	3,193	36	0	1,592	1,716	40	0	1,831	1,967
5-10	20	93	0	4,320	4,636	57	0	2,314	2,509	62	0	2,640	2,852
10-15	36	168	0	6,920	7,493	86	0	1,861	2,153	147	0	7,596	8,098
15-20	53	243	0	10,528	11,357	97	0	1,020	1,351	212	0	8,744	9,467
20-25	79	365	0	14,708	15,954	255	0	8,998	9,869	318	0	3,201	4,286
25-30	118	556	68	20,882	22,849	506	0	17,281	19,008	438	0	5,691	7,186
30-35	198	915	306	21,793	25,221	757	41	19,178	21,803	619	20	14,461	16,594
35-40	213	1,015	139	34,236	37,838	903	25	27,497	30,604	612	205	14,607	16,900
40-45	169	800	80	21,752	24,562	608	75	18,831	20,980	302	96	10,003	11,129
45-50	160	750	0	20,647	23,207	480	0	13,681	15,319	374	0	10,437	11,713
50-55	166	780	250	15,151	18,062	552	62	9,902	11,850	393	207	7,182	8,731
55-60	171	799	2,553	9,524	14,805	607	1,664	7,345	11,082	547	2,117	8,182	12,165
60-65	189	887	9,989	11,233	24,250	543	8,950	6,464	17,266	519	6,772	5,976	14,520
65-70	200	935	26,685	4,884	34,762	508	18,396	4,298	24,428	491	20,286	1,667	23,630
70-75	238	1,102	38,136	3,003	44,901	799	36,464	1,530	40,720	753	32,453	1,569	36,592
75-80	283	1,308	56,631	1,211	62,307	1,042	47,698	816	52,070	989	47,610	668	51,652
80-85	249	1,138	62,102	298	66,286	911	46,900	242	50,249	812	51,077	167	54,014
85-90	160	730	44,339	98	46,928	652	33,675	0	35,900	662	45,117	101	47,475
90-95	60	273	19,076	0	20,006	258	17,093	0	17,972	271	20,404	0	21,329
95-100	12	54	3,503	0	3,687	52	3,517	0	3,693	54	5,842	0	6,027
Total	2,795	13,009	263,857	206,177	514,434	9,729	214,560	143,911	391,676	8,638	232,205	105,954	367,642
Reduction (relative to mode 0)						25.2%	18.7%	30.2%	23.9%	33.6%	12.0%	48.6%	28.5%

Table D-12. CERL AHU-2 Total Fan and BTU Meter Energy Savings for the Historic Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
-10--5	4	4	0	1,485	1,498	0	0	1,345	1,346	0	0	855	855
-5-0	4	4	0	1,422	1,435	0	0	1,268	1,269	0	0	811	811
0-5	13	12	0	4,417	4,460	1	0	3,872	3,876	0	0	2,489	2,489
5-10	20	19	0	6,481	6,547	2	0	5,573	5,579	0	0	3,606	3,606
10-15	36	37	0	12,530	12,658	3	0	19,078	19,089	0	0	0	0
15-20	53	56	0	9,678	9,870	26	0	12,498	12,587	0	0	19,139	19,139
20-25	79	72	0	3,214	3,459	19	0	9,440	9,505	14	0	18,085	18,133
25-30	118	109	0	5,229	5,601	23	0	22,243	22,323	14	0	17,298	17,344
30-35	198	116	0	60,105	60,500	30	21	28,484	28,606	40	18	17,083	17,237
35-40	213	201	0	75,251	75,938	28	49	28,861	29,006	44	92	19,146	19,388
40-45	169	165	56	57,992	58,612	25	23	15,005	15,114	32	11	12,498	12,619
45-50	160	180	109	54,727	55,451	34	219	9,169	9,504	37	159	7,711	7,996
50-55	166	187	364	60,288	61,292	61	374	10,566	11,149	46	366	12,127	12,648
55-60	171	173	1,203	64,741	66,533	66	1,052	13,116	14,393	69	1,182	10,811	12,228
60-65	189	228	3,074	28,932	32,785	73	2,993	10,566	13,807	71	2,498	6,013	8,754
65-70	200	206	6,901	27,762	35,367	95	5,281	2,724	8,328	79	4,734	5,118	10,122
70-75	238	244	9,277	19,096	29,207	158	9,223	3,376	13,137	145	7,863	13,875	22,233
75-80	283	277	12,735	18,938	32,619	195	11,830	2,055	14,550	201	10,897	5,897	17,480
80-85	249	246	13,056	848	14,742	162	10,711	174	11,439	169	10,831	6,419	17,827
85-90	160	140	8,578	0	9,056	120	8,423	0	8,834	139	7,993	0	8,466
90-95	60	49	3,448	0	3,617	53	3,515	0	3,697	59	3,500	0	3,702
95-100	12	8	654	0	681	11	733	0	772	12	764	0	806
Total	2,795	2,735	59,456	513,136	581,926	1,187	54,446	199,412	257,910	1,170	50,908	178,978	233,881
Reduction (relative to mode 0)						56.6%	8.4%	61.1%	55.7%	57.2%	14.4%	65.1%	59.8%

Table D-13. Fort Bragg AHU-1 Total Fan and BTU Meter Energy Savings for the Historic Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10	1	2	0	70	77	0	0	78	78	0	0	0	0
10-15	3	7	0	193	215	0	0	215	216	0	0	0	1
15-20	15	34	0	902	1,017	7	0	1036	1058	2	132	45	182
20-25	38	85	0	1742	2,031	4	0	1315	1328	2	0	369	377
25-30	79	179	0	2723	3,334	11	0	2746	2784	9	0	1620	1,650
30-35	154	369	14	4048	5,321	21	141	3223	3434	15	39	2693	2,782
35-40	216	491	9	5424	7,106	21	247	3177	3496	29	143	3969	4,210
40-45	244	568	173	2724	4,835	30	328	3937	4366	20	229	2098	2,396
45-50	206	437	1167	887	3,544	23	613	1713	2406	19	168	1045	1,277
50-55	285	595	2306	1541	5,877	28	722	805	1622	23	748	747	1,574
55-60	286	612	3952	1133	7,174	26	1097	445	1632	25	910	179	1,176
60-65	354	713	7178	187	9,797	29	2081	148	2330	43	2296	54	2,495
65-70	435	911	13641	43	16,792	48	5845	45	6053	49	6052	186	6,406
70-75	392	840	16473	126	19,465	55	10924	126	11237	79	11161	141	11,572
75-80	340	740	18836	70	21,430	64	13860	181	14259	46	14801	110	15,069
80-85	135	303	9406	37	10,477	22	6052	43	6169	24	5899	46	6,029
85-90	54	124	3764	16	4,201	9	2828	20	2880	14	2931	22	3,001
90-95	13	30	1081	5	1,189	1	728	5	737	1	826	5	836
95-100	1	2	99	1	107	0	49	0	50	0	50	1	51
Total	3,251	7,041	78,097	21,869	123,991	399	45,517	19,257	66,135	401	46,386	13,330	61,084
Reduction (relative to mode 0)						94.3%	41.7%	11.9%	46.7%	94.3%	40.6%	39.0%	50.7%

Table D-14. Fort Bragg AHU-2 Total Fan and BTU Meter Energy Savings for the Historic Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10	1	2	0	19	0	1	0	19	0	1	0	15	0
10-15	3	7	0	52	0	2	0	53	0	2	0	40	0
15-20	15	35	0	238	355	0	0	236	236	0	142	130	272
20-25	38	87	0	546	845	0	0	526	526	0	0	428	428
25-30	79	182	0	1021	1,641	35	0	1322	1442	15	0	756	806
30-35	154	372	0	1271	2,541	47	0	1968	2128	90	0	1714	2,022
35-40	216	493	0	2738	4,419	151	633	865	2014	84	85	2923	3,295
40-45	244	545	1363	2525	5,747	174	526	2083	3204	178	286	2493	3,385
45-50	206	460	1920	1262	4,751	95	936	1221	2480	134	520	1036	2,014
50-55	285	639	3255	2163	7,598	253	1320	1583	3766	216	1501	1582	3,821
55-60	286	638	5263	992	8,431	295	3055	1369	5431	291	2089	975	4,056
60-65	354	773	8671	350	11,658	330	4759	603	6488	362	6250	287	7,771
65-70	435	974	14507	149	17,980	379	11892	185	13370	390	10555	777	12,663
70-75	392	891	16185	391	19,616	361	14929	280	16441	335	13874	1314	16,330
75-80	340	779	16319	265	19,243	369	16302	524	18084	356	16616	794	18,624
80-85	135	308	7628	116	8,796	152	7038	486	8041	146	7071	385	7,953
85-90	54	123	3054	44	3,519	55	3245	301	3733	61	3303	345	3,857
90-95	13	30	914	19	1,036	16	900	25	979	13	967	23	1,033
95-100	1	3	78	1	88	1	54	2	60	1	74	2	81
Total	3,251	7,341	79,158	14,160	118,266	2,716	65,588	13,652	88,423	2,674	63,334	16,017	88,411
Reduction (relative to mode 0)						63.0%	17.1%	3.6%	25.2%	63.6%	20.0%	-13.1%	25.2%

Table D-15. Fort Bragg AHU-3 Total Fan and BTU Meter Energy Savings for the Historic Weather-Normalized Data Set

Temperature Bins (F)	Bin Hours	Annual Mode 0 Energy				Annual Mode 1 Energy				Annual Mode 2 Energy			
		Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu	Fan kWh	ChW kBtu	HW kBtu	Total kBtu
5-10	1	2	0	58	64	0	0	76	77	0	0	30	30
10-15	3	6	0	157	176	1	0	197	199	1	0	82	84
15-20	15	28	0	737	833	1	0	1067	1070	0	189	297	486
20-25	38	71	0	1860	2,104	1	0	1132	1137	1	0	983	988
25-30	79	147	20	2897	3,418	2	8	2758	2773	0	5	1678	1,684
30-35	154	291	62	3432	4,488	2	198	2475	2682	1	64	2776	2,844
35-40	216	376	113	4701	6,096	5	520	3142	3679	1	236	3875	4,116
40-45	244	451	264	3295	5,099	6	620	2953	3592	1	413	3084	3,501
45-50	206	397	1099	2051	4,505	3	911	1783	2704	2	492	1650	2,148
50-55	285	532	2389	4122	8,327	23	1240	1615	2933	13	1206	1925	3,177
55-60	286	550	4080	2349	8,305	31	2437	1112	3657	67	1746	969	2,944
60-65	354	684	9279	576	12,189	64	3921	596	4735	91	5091	392	5,795
65-70	435	843	16591	188	19,655	74	11989	265	12507	117	10979	982	12,361
70-75	392	775	19118	479	22,242	78	17197	539	18001	105	15819	1000	17,177
75-80	340	637	21478	460	24,111	100	19606	1094	21041	117	20524	1135	22,059
80-85	135	266	10565	189	11,662	38	8456	380	8966	50	8630	427	9,226
85-90	54	100	3977	81	4,400	14	3614	178	3838	18	3873	218	4,151
90-95	13	17	1028	29	1,114	6	1038	53	1111	5	1153	53	1,224
95-100	1	2	102	1	111	1	65	4	72	1	83	4	90
Total	3,251	6,175	90,165	27,663	138,899	450	71,820	21,420	94,775	593	70,504	21,559	94,086
Reduction (relative to mode 0)						92.7%	20.3%	22.6%	31.8%	90.4%	21.8%	22.1%	32.3%

APPENDIX E MULTIZONE RETROFIT QUESTIONNAIRE SUMMARY REPORT

An online questionnaire was distributed to installation energy managers throughout the Department of Defense in order to gain better insight into the quantity and quality of multizone air handlers in use throughout the branches of service and how much interest there is in the CERL retrofit technique described in ESTCP project report EW-201152. The information in Table E-1 was gathered from 78 individual responses:

Table E-1. Survey Response Summary

	Army	Air Force	Navy
# of Responses	47	27	4
Total Annual Energy Consumption at Installations (BBTU)	21102	15452	2470
# of Buildings with HVAC	10,252 – 16,350	4,529 – 9,325	353 – 800
# of MZ AHUs	2,597 – 3,266	1,293 – 1,665	26 – 35
MZ Condition for Majority of Units	Major Repair: 3 Moderate Repair: 9 Minor Repair: 9 Need Little or No Work: 6	Major Repair: 5 Moderate Repair: 7 Minor Repair: 4 Need Little or No Work: 0	Major Repair: 0 Moderate Repair: 0 Minor Repair: 1 Need Little or No Work: 1
Level of Interest in MZ-to-VAV Retrofit	Very Interested: 16 Moderately Interested: 4 Somewhat Interested: 6 Not Interested: 3	Very Interested: 7 Moderately Interested: 3 Somewhat Interested: 4 Not Interested: 2	Very Interested: 2 Moderately Interested: 1 Somewhat Interested: 0 Not Interested: 0

This report shows that, just at the installations that responded to the questionnaire, there are between 3900 and 5000 multizone air handlers in use. 84% of the respondents verified that their multizone air handlers needed at least minor repairs or controls upgrades. Considering this feedback, coupled with the fact that 90% of respondents said they were at least somewhat interested in CERL's MZ-to-VAV retrofit process, there is already the potential for this retrofit process to be implemented at 2900 to 3800 multizone air handlers across the Department of Defense.

The full questionnaire is available online at https://www.surveymonkey.com/r/MZ-Questionnaire.

APPENDIX F AS-BUILT SEQUENCES OF OPERATION

F-1 CERL AHU-1 Sequence Of Operation

DDC HARDWARE AND SOFTWARE PERFORMS THIS SEQUENCE OF OPERATION. INPUTS, OUTPUTS, SETPOINTS, AND ALARM POINTS ARE SHOWN ON THE POINTS SCHEDULE DRAWING. UNLESS OTHERWISE SPECIFIED, ALL MODULATING CONTROL IS PROPORTIONAL-INTEGRAL (PI) CONTROL.

TEST MODES. THE AIR HANDLING SYSTEM OPERATES IN ONE OF THREE TEST MODES: BASIC, ADVANCED 1, OR ADVANCED 2. THE THREE TEST MODES ARE DELINEATED IN THE 'TABLE OF CONTROL LOOP OPTIONS BY TEST MODE'. THE NIAGARA FRONT-END WORKSTATION ROTATES THE UNIT THROUGH THE TEST MODES, CHANGING MODES DAILY AT MIDNIGHT.

A. HAND-OFF-AUTO SWITCHES: THE SUPPLY FAN VARIABLE FREQUENCY DRIVE (VFD) HAS AN INTEGRAL H-0-A SWITCH:
(1) HAND: WITH THE H-0-A SWITCH IN HAND POSITION, THE SUPPLY FAN STARTS AND RUNS CONTINUOUSLY, SUBJECT TO SAFETIES, AT A MANUALLY ADJUSTABLE SPEED.
(2) OFF: WITH THE H-0-A SWITCH IN OFF POSITION, THE SUPPLY FAN STOPS.
(3) AUTO: WITH THE H-0-A SWITCH IN AUTO POSITION, THE SUPPLY FAN RUNS, SUBJECT TO THE SUPPLY FAN START/STOP COMMAND AND SAFETIES, ACCORDING TO THE SUPPLY FAN (SPEED) COMMAND (AND THE FAN CAPACITY CONTROL LOOP.

B. OCCUPANCY MODES: THE SYSTEM ACCEPTS OCCUPANCY MODE COMMANDS FROM THE NETWORK AND TEMPORARY OCCUPANCY OVERRIDES FROM THE ZONES AS INDICATED BELOW. THE SYSTEM OPERATES IN ONE OF THE FOLLOWING MODES: OCCUPIED, UNOCCUPIED, OR WARMUP/ COOLDOWN. IN EACH OCCUPANCY MODE, THE SYSTEM OPERATES AS INDICATED IN THE "TABLE OF ENABLED LOOPS".
(1) OCCUPIED / UNOCCUPIED MODE. THE NIAGARA FRONT-END WORKSTATION COMMANDS THE SYSTEM TO OCCUPIED OR UNOCCUPIED ACCORDING TO THE NIAGARA FRONT-END OCCUPANCY SCHEDULE. UPON LOSS OR ABSENCE OF THE NIAGARA OCCUPANCY COMMAND THE 'BACKUP SCHEDULER' WILL COMMAND THE SYSTEM TO UNOCCUPIED AND OCCUPIED MODE.
(2) UNOCCUPIED. IF ANY ZONE THERMOSTAT SENSES AIR TEMPERATURE ABOVE 85 DEG F OR BELOW 55 DEG F THE AHU WILL START AND RUN, UNTIL THE TEMPERATURE AT THAT THERMOSTAT DROPS OR RISES 5 DEG F.
(3) WARMUP/COOLDOWN MODE. ONE HOUR BEFORE SCHEDULED OCCUPIED MODE THE UNIT WILL BE ENABLED TO GO INTO WU/CD DEPENDING ON SPACE TEMPERATURE WHERE:
-COOLDOWN: IF ANY SPACE IS ABOVE 76 DEG F THE UNIT WILL START.
-WARMUP: IF ANY SPACE IS BELOW 68 DEG F THE UNIT WILL START.

C. PROOFS AND SAFETIES: THE SUPPLY AND RETURN FAN AND DDC HARDWARE LOOPS ARE SUBJECT TO PROOFS AND SAFETIES. SAFETIES ARE DIRECT-HARDWIRE INTERLOCKED TO THE FAN START CIRCUIT. FAILURE OF ANY PROOF RESULTS IN THE CONTORL LOOPS BEING DISABLED. ACTIVATION OF ANY SAFETY RESULTS IN ALL CONTROL LOOPS BEING DISABLED AND THE AHU FAN BEING COMMANDED OFF UNTIL RESET. ACTIVATION OF THE TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL) ENABLES HOT DECK COIL CONTROL AT A HOT DECK TEMPERATURE SETPOINT OF 75 DEG F. DDC HARDWARE RESET OF SAFETIES IS VIA PUSH-BUTTON LOCATED INSIDE THE CONTROL PANEL IN THE N.E. CORNER OF ROOM 2014.
(1) PROOFS:
i. SUPPLY FAN STATUS (PROOF) (SF-S)
ii. RETURN FAN STATUS (PROOF) (RF-S)
(2) SAFETIES
i. TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL-1)
ii. RETURN AIR SMOKE (RA-SMK)
iii. RETURN DUCT DIFFERENTIAL PRESSURE SWITCH HIGH (DPSH-1) LIMIT SWITCH

D. FAN CAPACITY CONTROL
(1) WHEN DISABLED: WHEN THIS LOOP IS DISABLED THE FAN IS COMMANDED OFF.
(2) WHEN ENABLED: FAN CAPACITY CONTROL IS EITHER CONSTANT OR VARIABLE FAN SPEED CONTROL BASED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE".
i. CONSTANT FAN SPEED: THE SUPPLY FAN WILL SOFT START (SLOWLY RAMP) TO 100% SPEED AND MAINTAIN THIS SPEED.
ii. VARIABLE FAN SPEED: AS DESCRIBED BELOW
(3) VARIABLE FAN SPEED: THE SUPPLY FAN WILL SOFT START (SLOWLY RAMP) THEN MODULATE BASED ON THE ZONE DAMPER COMMAND FOR EACH ZONE AS COMPARED TO THE DAMPER POSITION SETPOINT (ZN-D-SP) OF 5% AND 95%. THE PROCESS VARIABLE FOR THIS LOOP IS MINIMUM (AND) MAXIMUM ZONE DAMPER COMMAND DETERMINED AS FOLLOWS:
i. STEP 1: DETERMINE THE DAMPER COMMANDED TO BE MOST OPEN TO COOLING: ZN-D-MAX
ii. STEP 2: DETERMINE THE DAMPER COMMANDED TO BE MOST OPEN TO HEATING: ZN-D-MIN
iii. STEP 3: THE MOST OPEN DAMPER (% COMMAND) FROM STEPS 1 AND 2 IS THE PROCESS VARIABLE FOR THE PI CONTROL LOOP.
SUPPLY FAN SPEED WILL NOT DROP BELOW THE MINIMUM SUPPLY FAN SPEED OF 25% (CONFIGURED AT THE VFD) OR BELOW THE FAN SPEED SET BY THE 'PRE-EMPTIVE FREEZE PROTECTION' DESCRIBED UNDER PARA E 'OUTSIDE AIR FLOW CONTROL', OR BELOW THE SPEED NECESSARY TO ACHIEVE THE MINIMUM OUTSIDE AIR FLOW QUANTITY.
(4) RETURN FAN CONTROL. RETURN FAN COMMAND (RF-C) IS 5% LESS THAN SUPPLY FAN COMMAND (SF-C).

E. OUTSIDE AIR FLOW CONTROL
(1) WHEN DISABLED: THE OUTSIDE AIR DAMPER IS CLOSED
(2) WHEN ENABLED: CONTROL OUTSIDE AIR DAMPER AS INDICATED IN "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE" AND FOR PRE-EMPTIVE FREEZE PROTECTION:
i. FIXED DAMPER POSITION: THE OUTSIDE AIR (OA) DAMPER IS COMMANDED TO THE FIXED POSITION THAT CORRESPONDS TO AN OA FLOW OF 5,000 CFM.
ii. FIXED FLOW SETPOINT: THE OUTSIDE AIR DAMPER MODULATES TO MAINTAIN THE OA FLOW AT A FIXED SETPOINT OF 5,000 CFM.
iii. DEMAND CONTROL VENTILATION: THE DDC HARDWARE MODULATES THE OUTSIDE AIR DAMPER TO MAINTAIN THE OA VOLUMETRIC FLOW AT SETPOINT BASED ON THE MAXIMUM C02 SENSED IN ANY AREA/SPACE SERVED BY THE AHU USING PI CONTROL OF THE OA FLOW ACCORDING TO THE FOLLOWING SETPOINT RESET SCHEDULE:

MAXZONEC02	OA FLOW SETPOINT
500 PPM	1,000 CFM (LOWER LIMIT)
1,000 PPM	5,000 CFM (UPPER LIMIT)

(3) PRE-EMPTIVE FREEZE PROTECTION / MIXED AIR LOW LIMIT (MALL): AS MIXED AIR TEMPERATURE DROPS, THE FAN SPEEDS UP TO PULL MORE RETURN AIR AND THEN THE OA DAMPER MOVES TOWARDS CLOSED. THIS IS ACCOMPLISHED THROUGH 2 LOOPS: MINIMUM FAN SPEED IS INCREASED VIA REVERSE ACTING P-ONLY LOOP WITH A 4 DEG F THROTTLING RANGE AND SETPOINT 2 DEG ABOVE THE MALL-T-SP (i.e. 50 DEG F). MAXIMUM DAMPER POSITION IS SET VIA DIRECT ACTING P-ONLY LOOP WITH A 4 DEG F THROTTLING RANGE AND SETPOINT 2 DEG F BELOW THE MALL-T-SP (i.e. 46 DEG F).

F. AIR SIDE ECONOMIZER:

(1) WHEN DISABLED: ECONOMIZER IS OFF

(2) WHEN ENABLED:

i. THE ECONOMIZER IS ON WHEN THE COLD DECK IS ON AND THE OUTSIDE AIR DRY BULB TEMPERATURE IS BETWEEN THE HIGH LIMIT (ECO-HL-SP) AND LOW LIMIT (ECO-LL-SP) SETPOINTS, EACH WITH A 2 DEGREE F DEADBAND.

ii. ECONOMIZER IS OFF OTHERWISE

iii. WHEN ECONOMIZER IS ON, THE OUTSIDE, RELIEF, AND RETURN AIR DAMPERS MODULATE TO MAINTAIN THE COLD DECK TEMPERATURE AT SETPOINT (CD-T-SP). DAMPER COMMAND DOES NOT DROP BELOW THAT REQUIRED TO MAINTAIN OUTSIDE AIR FLOW CONTROL.

G. HOT DECK TEMPERATURE CONTROL:

(1) WHEN DISABLED: THE HOT DECK VALVE CONTROL IS OFF WHEN ENABLED:

(2) WHEN ENABLED:

i. HOT DECK 'VALVE CONTROL' IS ON OR OFF IN ACCORDANCE WITH THE TABLE OF CONTROL LOOP OPTIONS BY TEST MODE

1. WHEN **ANY** ZONE DAMPER COMMAND IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-D-C < HTG-00-LL) HOT DECK VALVE CONTROL IS ON. THE VALVE CONTROL REMAINS ON UNTIL **ALL** ZONE DAMPER COMMAND SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (HTG-00-HL).

2. WHEN **ALL** ZONE DAMPER COMMAND SIGNALS (ZN-D-C) ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (HTG-00-HL) THE HOT DECK VALVE CONTROL IS OFF AND REMAIN OFFS UNTIL **ANY** ZONE DAMPER COMMAND (ZN-D-C) IS LESS THAN THE HEATING ON/OFF LOW LIMIT (HTG-00-LL).

3. HTG-00-LL AND HTG-00-HL ARE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:

A. HTG-00-LL: 25%

B. HTG-00-HL: 60%

ii. WHEN HOT DECK VALVE CONTROL IS OFF: HOT DECK HEATING COIL VALVE IS CLOSED

iii. WHEN HOT DECK VALVE CONTROL IS ON: THE VALVE MODULATES TO MAINTAIN THE HOT DECK TEMPERATURE (HD-T) AT SETPOINT (HD-T-SP). WHEN INDICATED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE", RESET HOT DECK SETPOINT (HD-T-SP) BASED ON OUTDOOR AIR TEMPERATURE USING A RESET SCHEDULE: WHEN THE OUTDOOR AIR TEMPERATURE IS LESS THAN OR EQUAL TO 50 DEG F THE HOT DECK TEMPERATURE SETPOINT IS 90 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN 50 DEGREES F THE HOT DECK TEMPERATURE SETPOINT IS 80 DEGREES F.

H. COLD DECK TEMPERATURE CONTROL

(1) WHEN DISABLED: THE COLD DECK VALVE CONTROL IS OFF

(2) WHEN ENABLED:

i. COLD DECK 'VALVE CONTROL' IS ON OR OFF IN ACCORDANCE WITH THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE".

1. WHEN **ANY** ZONE DAMPER COMMAND IS GREATER THAN THE COOLING ON/OFF LOW LIMIT (ANY ZN-D-C > CLG-00-HL) COLD DECK VALVE CONTROL IS ON. THE COLD DECK VALVE CONTROL REMAINS ON UNTIL **ALL** ZONE DAMPER COMMAND SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-D-C < CLG-00-LL).

2. WHEN **ALL** ZONE DAMPER COMMAND SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-D-C < CLG-00-LL) THE COLD DECK VALVE CONTROL IS OFF AND REMAINS OFF UNTIL **ANY** ZONE DAMPER COMMAND IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-D-C > CLG-00-HL).

3. CLG-00-LLAND CLG-00-HL ARE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:

A. CLG-00-LL: 25%

B. CLG-00-HL: 60%

ii. WHEN COLD DECK VALVE CONTROL IS OFF: COLD DECK COOLING COIL VALVE IS CLOSED.

iii. WHEN COLD DECK VALVE CONTROL IS ON: THE COLD DECK COOLING COIL VALVE MODULATES TO MAINTAIN THE COLD DECK TEMPERATURE (CD-T) AT SETPOINT (CD-T-SP).

K. ZONE TEMPERATURE CONTROL:

(1) THE ZONE TEMPERATURE SETPOINT (ZN-T-SP) IS AT THE GLOBAL ZONE TEMPERATURE SETPOINT (SELECTED BY THE BAS OPERATOR) OR AT THE OCCUPANT-ADJUSTABLE SETPOINT AT THE WALL-MOUNTED THERMOSTAT. GLOBAL VERSUS OCCUPANT-ADJUSTABLE CAPABILITY IS SELECTED BY THE BAS OPERATOR.

(2) THE HOT DECK AND COLD DECK DAMPERS MODULATE TO MAINTAIN ZONE TEMPERATURE (ZN-T) AT SETPOINT (ZN-T-SP). UPON A RISE IN ZONE TEMPERATURE ABOVE SETPOINT THE ZONE COLD DECK DAMPER MODULATES TOWARDS OPEN AS THE HOT DECK DAMPER MODULATES TOWARDS CLOSED. UPON A FALL IN ZONE TEMPERATURE BELOW SETPOINT THE HOT DECK DAMPER MODULATES TOWARDS OPEN AS THE COLD DECK DAMPER MODULATES TOWARDS CLOSED.

L. REHEAT COIL CONTROL (TYPICAL OF 3):

(1) PRE-EXISTING PNEUMATIC CONTROLS: THE REHEAT COIL IS CONTROLLED BY A WALL-MOUNTED PNEUMATIC THERMOSTAT IN EACH OF THE 3 CORRIDORS. AS THE CORRIDOR TEMPERATURE FALLS BELOW THE TEMPERATURE SETPOINT THE REHEAT COIL CONTROL VALVE MODULATES OPEN. WHEN THE CORRIDOR TEMPERATURE IS ABOVE SETPOINTTHE REHEAT VALVE MODULATES CLOSED.

F-2 CERL AHU-2 Sequence Of Operation

DDC HARDWARE AND SOFTWARE PERFORMS THIS SEQUENCE OF OPERATION. INPUTS, OUTPUTS, SETPOINTS, AND ALARM POINTS ARE SHOWN ON THE POINTS SCHEDULE DRAWING. UNLESS OTHERWISE SPECIFIED, ALL MODULATING CONTROL IS PROPORTIONAL-INTEGRAL (PI) CONTROL.

TEST MODES. THE AIR HANDLING SYSTEM OPERATES IN ONE OF THREE TEST MODES: BASIC, ADVANCED 1, OR ADVANCED 2. THE THREE TEST MODES ARE DELINEATED IN THE 'TABLE OF CONTROL LOOP OPTIONS BY TEST MODE'. THE NIAGARA FRONT-END WORKSTATION ROTATES THE UNIT THROUGH THE TEST MODES, CHANGING MODES DAILY AT MIDNIGHT.

A. HAND-OFF-AUTO SWITCHES: THE SUPPLY FAN VARIABLE FREQUENCY DRIVE (VFD) HAS AN INTEGRAL H-0-A SWITCH:
(1) HAND: WITH THE H-0-A SWITCH IN HAND POSITION, THE SUPPLY FAN STARTS AND RUNS CONTINUOUSLY, SUBJECT TO SAFETIES, AT A MANUALLY ADJUSTABLE SPEED.
(2) OFF: WITH THE H-0-A SWITCH IN OFF POSITION, THE SUPPLY FAN STOPS.
(3) AUTO: WITH THE H-0-A SWITCH IN AUTO POSITION, THE SUPPLY FAN RUNS, SUBJECT TO THE SUPPLY FAN START/STOP COMMAND AND SAFETIES, ACCORDING TO THE SUPPLY FAN (SPEED) COMMAND (AND THE FAN CAPACITY CONTROL LOOP.

B. OCCUPANCY MODES: THE SYSTEM ACCEPTS OCCUPANCY MODE COMMANDS FROM THE NETWORK AND TEMPORARY OCCUPANCY OVERRIDES FROM THE ZONES AS INDICATED BELOW. THE SYSTEM OPERATES IN ONE OF THE FOLLOWING MODES: OCCUPIED, UNOCCUPIED, OR WARMUP/COOLDOWN. IN EACH OCCUPANCY MODE, THE SYSTEM OPERATES AS INDICATED IN THE "TABLE OF ENABLED LOOPS".
(1) OCCUPIED / UNOCCUPIED MODE. THE NIAGARA FRONT-END WORKSTATION COMMANDS THE SYSTEM TO OCCUPIED OR UNOCCUPIED ACCORDING TO THE NIAGARA FRONT-END OCCUPANCY SCHEDULE. UPON LOSS OR ABSENCE OF THE NIAGARA OCCUPANCY COMMAND THE 'BACKUP SCHEDULER' WILL COMMAND THE SYSTEM TO UNOCCUPIED AND OCCUPIED MODE.
(2) UNOCCUPIED. IF ANY ZONE THERMOSTAT SENSES AIR TEMPERATURE ABOVE 85 DEG F OR BELOW 55 DEG F THE AHU WILL START AND RUN, UNTIL THE TEMPERATURE AT THAT THERMOSTAT DROPS OR RISES 5 DEG F.
(3) WARMUP/COOLDOWN MODE. ONE HOURR BEFORE SCHEDULED OCCUPIED MODE THE UNIT WILL BE ENABLED TO GO INTO WU/CD DEPENDING ON SPACE TEMPERATURE WHERE:
-COOLDOWN: IF ANY SPACE IS ABOVE 76 DEG F THE UNIT WILL START.
-WARMUP: IF ANY SPACE IS BELOW 68 DEG F THE UNIT WILL START.

C. PROOFS AND SAFETIES: THE SUPPLY FAN AND DDC HARDWARE LOOPS ARE SUBJECT TO PROOFS AND SAFETIES. SAFETIES ARE DIRECT-HARDWIRE INTERLOCKED TO THE FAN START CIRCUIT. FAILURE OF ANY PROOF RESULTS IN ALL CONTROL LOOPS BEING DISABLED. ACTIVATION OF ANY SAFETY RESULTS IN ALL CONTROL LOOPS BEING DISABLED AND THE AHU FAN BEING COMMANDED OFF UNTIL RESET. ACTIVATION OF THE TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL) ENABLES HOT DECK COIL CONTROL AT A HOT DECK TEMPERATURE SETPOINT OF 75 DEG F. DDC HARDWARE RESET OF SAFETIES IS VIA PUSH-BUTTON LOCATED ON THE DOOR OF THE CONTROL PANEL ALONG THE WEST WALL OF ROOM 2127.

-DDC SOFTWARE RESET OF PROOFS AND SAFETIES IS VIA PUSH-BUTTON ON THE FRONT OF THE CONTROL PANEL DOOR.
(1) PROOFS:
i. SUPPLY FAN STATUS (PROOF) (SF-S)
(2) SAFETIES
i. TEMPERATURE LOW LIMIT (T-LL) (FREEZE STAT). THE T-LL DOES NOT HAVE ITS OWN PUSH BUTTON RESET.

-HARDWARE RESET OF SAFETIES IS VIA LOCAL PUSH-BUTTON AT THE DEVICE.
(1) SAFETIES
i. SMOKE ALARM

D. FAN CAPACITY CONTROL
(1) WHEN DISABLED: WHEN THIS LOOP IS DISABLED THE FAN IS COMMANDED OFF.
(2) WHEN ENABLED: FAN CAPACITY CONTROL IS EITHER CONSTANT OR VARIABLE FAN SPEED CONTROL BASED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE".
i. CONSTANT FAN SPEED: THE SUPPLY FAN WILL SOFT START (SLOWLY RAMP) TO 100% SPEED AND MAINTAIN THIS SPEED.
ii. VARIABLE FAN SPEED: AS DESCRIBED BELOW
(3) VARIABLE FAN SPEED: SOFT START (SLOWLY RAMP) THE SUPPLY FAN THEN MODULATE THE FAN SPEED COMMAND BASED ON THE ZONE DAMPER COMMAND FOR EACH ZONE AS COMPARED TO THE DAMPER POSITION SETPOINT (ZN-D-SP) OF 5% AND 95%. THE PROCESS VARIABLE FOR THIS LOOP IS MINIMUM (AND) MAXIMUM ZONE DAMPER COMMAND DETERMINED AS FOLLOWS:
i. STEP 1: DETERMINE THE DAMPER COMMANDED TO BE MOST OPEN TO COOLING: ZN-D-MAX
ii. STEP 2: DETERMINE THE DAMPER COMMANDED TO BE MOST OPEN TO HEATING: ZN-D-MIN
iii. STEP 3: THE MOST OPEN DAMPER (% COMMAND) FROM STEPS 1 AND 2 IS THE PROCESS VARIABLE FOR THE PI CONTROL LOOP.

SUPPLY FAN SPEED WILL NOT DROP BELOW THE MINIMUM SUPPLY FAN SPEED OF 25% OR BELOW THE FAN SPEED SET BY THE 'PRE-EMPTIVE FREEZE PROTECTION' DESCRIBED UNDER PARA E 'OUTSIDE AIR FLOW CONTROL', OR BELOW THE SPEED NECESSARY TO ACHIEVE THE MINIMUM OUTSIDE AIR FLOW QUANTITY.

E. OUTSIDE AIR FLOW CONTROL

(1) WHEN DISABLED: THE OUTSIDE AIR (OA) DAMPER IS CLOSED

(2) WHEN ENABLED: CONTROL OUTSIDE AIR DAMPER AS INDICATED IN "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE" AND FOR PRE-EMPTIVE FREEZE PROTECTION:

i. FIXED DAMPER POSITION: THE OUTSIDE AIR (OA) DAMPER IS COMMANDED TO THE FIXED POSITION THAT CORRESPONDS TO AN OA FLOW OF 450 CFM.

ii. FIXED FLOW SETPOINT: THE OUTSIDE AIR DAMPER MODULATES TO MAINTAIN THE OA FLOW AT A FIXED SETPOINT OF 450 CFM.

iii. DEMAND CONTROL VENTILATION: MODULATE THE OUTSIDE AIR DAMPER TO MAINTAIN THE OA VOLUMETRIC FLOW AT SETPOINT (OA-F-SP) BASED ON THE OCCUPANCY SENSED IN CONFERENCE ROOMS 2103, 2104, AND 2107. IF NO CONFERENCE ROOMS ARE OCCUPIED AS SENSED BY THE CEILING-MOUNTED OCCUPANCY SENSORS OA-F-SP IS 290 CFM. IF ANY ONE OR MORE OF THE CONFERENCE ROOMS ARE OCCUPIED AS SENSED BY ANY OF THE CEILING-MOUNTED OCCUPANCY SENSORS THEN OA-F-SP IS RESET TO 450 CFM.

(4) PRE-EMPTIVE FREEZE PROTECTION / MIXED AIR LOW LIMIT (MALL): AS PREHEAT COIL DISCHARGE AIR TEMPERATURE DROPS, THE FAN SPEEDS UP TO PULL MORE RETURN AIR, THE PREHEAT COIL VALVE MODULATES OPEN, AND THEN THE OA DAMPER MOVES TOWARDS CLOSED, ALL IN SEQUENCE. THIS IS ACCOMPLISHED THROUGH 3 LOOPS: MINIMUM FAN SPEED IS SET VIA REVERSE ACTING P-ONLY LOOP WITH A 4 DEG F THROTTLING RANGE AND SETPOINT 2 DEG ABOVE THE MALL-T-SP (i.e. 50 DEGF). PREHEAT VALVE IS PLACED UNDER CONTROL, WHEN ENABLED. MAXIMUM DAMPER POSITION IS SET VIA A DIRECT ACTING P-ONLY LOOP WITH A 4 DEG THROTTLING RANGE AND SETPOINT 2 DEG F BELOW THE MALL-T-SP (i.e. 46 DEG).

F. AIR SIDE ECONOMIZER:

(1) WHEN DISABLED: ECONOMIZER IS OFF.

(2) WHEN ENABLED:

i. THE ECONOMIZER IS ON WHEN THE COLD DECK IS ON AND THE OUTSIDE AIR DRY BULB TEMPERATURE IS BETWEEN THE HIGH LIMIT (ECO-HL-SP) AND LOW LIMIT (ECO-LL-SP) SETPOINTS, EACH WITH A 2 DEGREE F DEADBAND.

ii. ECONOMIZER IS OFF OTHERWISE

iii. WHEN ECONOMIZER IS ON, THE OUTSIDE, RELIEF, AND RETURN AIR DAMPERS MODULATE TO MAINTAIN THE COLD DECK TEMPERATURE AT SETPOINT (CD-T-SP). DAMPER COMMAND DOES NOT DROP BELOW THAT REQUIRED TO MAINTAIN OUTSIDE AIR FLOW CONTROL.

G. HOT DECK TEMPERATURE CONTROL:

(1) WHEN DISABLED: THE HOT DECK VALVE CONTROL IS OFF WHEN ENABLED:

(2) WHEN ENABLED:

i. HOT DECK 'VALVE CONTROL' IS ON OR OFF IN ACCORDANCE WITH THE 'TABLE OF CONTROL LOOP OPTIONS BY TEST MODE' (ALSO SEE THE DIAGRAM ILLUSTRATING HOT DECK ON/OFF ON NEXT DRAWING SHEET):

1. WHEN **ANY** ZONE DAMPER COMMAND IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-D-C < HTG-00-LL) HOT DECK VALVE CONTROL IS ON. THE VALVE CONTROL REMAINS ON UNTIL **ALL** ZONE DAMPER COMMAND SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (HTG-00-HL).

2. WHEN **ALL** ZONE DAMPER COMMAND SIGNALS (ZN-D-C) ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (HTG-00-HL) THE HOT DECK VALVE CONTROL IS OFF AND REMAIN OFFS UNTIL **ANY** ZONE DAMPER COMMAND (ZN-D-C) IS LESS THAN THE HEATING ON/OFF LOW LIMIT (HTG-00-LL).

3. HTG-00-LL AND HTG-00-HL ARE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:

A. HTG-00-LL: 25%

B. HTG-00-HL: 60%

ii. WHEN HOT DECK VALVE CONTROL IS OFF: HOT DECK HEATING COIL VALVE IS CLOSED

iii. WHEN HOT DECK VALVE CONTROL IS ON: THE HOT DECK HEATING COIL VALVE MODULATES TO MAINTAIN THE HOT DECK TEMPERATURE (HD-T) AT SETPOINT (HD-T-SP). WHEN INDICATED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE", RESET HOT DECK SETPOINT (HD-T-SP) BASED ON OUTDOOR AIR TEMPERATURE USING A RESET SCHEDULE: WHEN THE OUTDOOR AIR TEMPERATURE IS LESS THAN OR EQUAL TO 50 DEG F THE HOT DECK TEMPERATURE SETPOINT IS 90 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN 50 DEGREES F THE HOT DECK TEMPERATURE SETPOINT IS 80 DEGREES F.

H. COLD DECK TEMPERATURE CONTROL

(1) WHEN DISABLED: THE COLD DECK VALVE CONTROL IS OFF

(2) WHEN ENABLED:

i. COLD DECK 'VALVE CONTROL' IS ON OR OFF IN ACCORDANCE WITH THE 'TABLE OF CONTROL LOOP OPTIONS BY TEST MODE' (ALSO SEE THE DIAGRAM ILLUSTRATING COLD DECK ON/OFF ON NEXT DRAWING SHEET):.

1. WHEN **ANY** ZONE DAMPER COMMAND IS GREATER THAN THE COOLING ON/OFF LOW LIMIT (ANY ZN-D-C > CLG-00-HL) COLD DECK VALVE CONTROL IS ON. THE COLD DECK VALVE CONTROL REMAINS ON UNTIL **ALL** ZONE DAMPER COMMAND SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-D-C < CLG-00-LL).

2. WHEN **ALL** ZONE DAMPER COMMAND SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-D-C < CLG-00-LL) THE COLD DECK VALVE CONTROL IS OFF AND REMAINS OFF UNTIL **ANY** ZONE DAMPER COMMAND IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-D-C > CLG-00-HL).

3. CLG-00-LLAND CLG-00-HL ARE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:

A. CLG-00-LL: 25%

B. CLG-00-HL: 60%

ii. WHEN COLD DECK VALVE CONTROL IS OFF: COLD DECK COOLING COIL VALVE IS CLOSED.

iii. WHEN COLD DECK VALVE CONTROL IS ON: THE COLD DECK COOLING COIL VALVE MODULATES TO MAINTAIN THE COLD DECK TEMPERATURE (CD-T) AT SETPOINT (CD-T-SP).

K. ZONE TEMPERATURE CONTROL (**ZONE 1**: ROOM 2108 & HALLWAY. **ZONE 2**: ROOMS 2107 AND 2111)

(1) THE ZONE TEMPERATURE SETPOINT (ZN-T-SP) IS AT THE BAS OPERATOR SELECTED GLOBAL ZONE TEMPERATURE SETPOINT. FOR ZONE 2 THE BAS OPERATOR CAN SELECT (PERMIT) OCCUPANT-ADJUSTABLE SETPOINT AT THE WALL-MOUNTED THERMOSTAT.

(2) THE HOT DECK AND COLD DECK DAMPERS MODULATE TO MAINTAIN ZONE TEMPERATURE (ZN-T) AT SETPOINT (ZN-T-SP). UPON A RISE IN ZONE TEMPERATURE ABOVE SETPOINT THE ZONE COLD DECK DAMPER MODULATES TOWARDS OPEN AS THE HOT DECK DAMPER MODULATES TOWARDS CLOSED. UPON A FALL IN ZONE TEMPERATURE BELOW SETPOINT THE HOT DECK DAMPER MODULATES TOWARDS OPEN AS THE COLD DECK DAMPER MODULATES TOWARDS CLOSED.

L. ZONE TEMPERATURE CONTROL (**ZONE 3**: ROOMS 2103 AND 2104)

(1) EACH ROOM HAS A THERMOSTAT. THE ZONE TEMPERATURE SETPOINT (ZN-T-SP) IS AT THE GLOBAL ZONE TEMPERATURE SETPOINT (SELECTED BY THE BAS OPERATOR) OR AT THE OCCUPANT-ADJUSTABLE SETPOINT AT THE WALL-MOUNTED THERMOSTAT, GLOBAL VERSUS OCCUPANT-ADJUSTABLE CAPABILITY IS SELECTED BY THE BAS OPERATOR.

(2) THE ROOM THERMOSTAT WITH THE GREATEST CALL FOR COOLING IS USED FOR TEMPERATURE CONTROL.

(3) THE HOT DECK AND COLD DECK DAMPERS MODULATE TO MAINTAIN ZONE TEMPERATURE (ZN-T) AT SETPOINT (ZN-T-SP). UPON A RISE IN ZONE TEMPERATURE ABOVE SETPOINT THE ZONE COLD DECK DAMPER MODULATES TOWARDS OPEN AS THE HOT DECK DAMPER MODULATES TOWARDS CLOSED. UPON A FALL IN ZONE TEMPERATURE BELOW SETPOINT THE HOT DECK DAMPER MODULATES TOWARDS OPEN AS THE COLD DECK DAMPER MODULATES TOWARDS CLOSED.

M. PREHEAT COIL CONTROL:

(1) WHEN DISABLED: THE PREHEAT VALVE IS CLOSED AND PREHEAT PUMP IS OFF.

(2) WHEN ENABLED: THE PREHEAT COIL VALVE MODULATES TO MAINTAIN PREHEAT COIL DISCHARGE AIR TEMPERATURE AT MA-T-LL-SP. WHEN THE PREHEAT COIL VALVE COMMAND IS OVER 5% THE PREHEAT PUMP STARTS. IF THE PREHEAT COIL VALVE COMMAND IS LESS THAN 1% THE PUMP OFF.

F-3 CERL AHU Sequence Tables And Diagrams

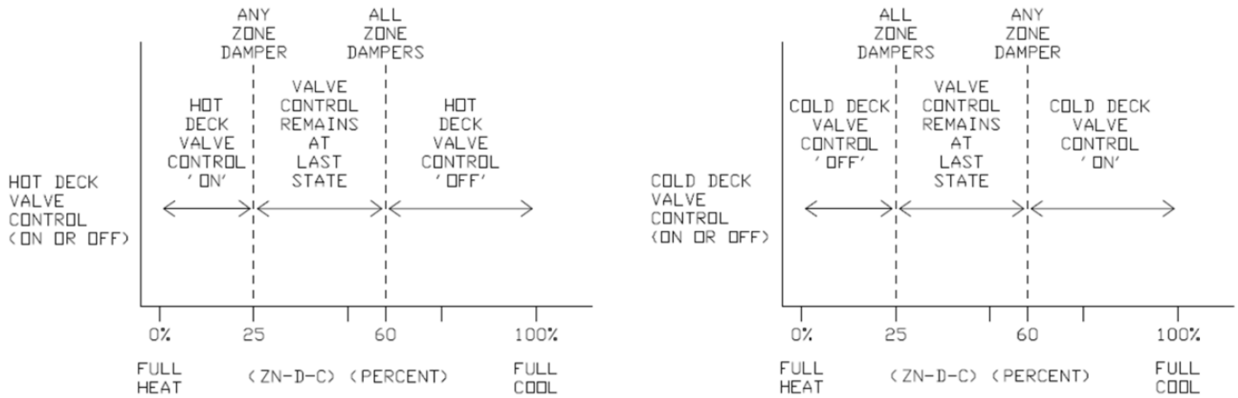
TABLE OF CONTROL LOOP OPTIONS BY TEST MODE

AHU/TEST MODE	FAN CAPACITY CONTROL		OUTSIDE AIR FLOW CONTROL			MIXED AIR LOW LIMIT CONTROL	MIXED AIR TEMP CONTROL WITH ECONOMIZER	HOT DECK TEMP CONTROL HD-T-SP		ZONE TEMP CONTROL	HALLWAY REHEAT COIL CONTROL	PREHEAT COIL CONTROL
	CONSTANT FAN SPEED	VARIABLE FAN SPEED	FIXED DAMPER POSITION	CONTROL TO FIXED FLOW SETPOINT	DEMAND CONTROL VENTILATION	MIXED AIR LOW LIMIT CONTROL	MIXED AIR TEMPERATURE CONTROL WITH ECONOMIZER	FIXED HD SETPOINT (NO RESET)	HD SETPOINT RESET BASED ON OA-T	ZONE TEMPERATURE CONTROL	REHEAT COIL CONTROL (AHU-2-001 ONLY)	PREHEAT COIL CONTROL (AHU-2-002 ONLY)
CERL AHU-2-001												
Basic Mode	X		X			X	X		X	X	X	
Advanced Mode #1		X		X		X	X	X		X	X	
Advanced Mode #2		X			X	X	X	X		X	X	
CERL AHU-2-002												
Basic Mode	X		X			X	X		X	X		X
Advanced Mode #1		X		X		X	X	X		X		X
Advanced Mode #2		X			X	X	X	X		X		X

TABLE OF ENABLED LOOPS BY OCCUPANCY MODE

MODES	FAN CAPACITY CONTROL	OA FLOW CONTROL LOOP	MIXED AIR LOW LIMIT	MIXED AIR TEMPERATURE CONTROL WITH ECONOMIZER	HD TEMPERATURE CONTROL	CD TEMPERATURE CONTROL	ZONE TEMPERATURE CONTROL	PREHEAT COIL CONTROL
OCCUPIED	X	X	X	X	X	X	X	X
UNOCCUPIED, MAX(ZN-T) > BLDG-T-HL (DEADBAND = 5 DEG F ADJUSTABLE)	X		X	X		X	X	X
UNOCCUPED, MAX(ZN-T) < BLDG-T-HL AND > BLDG-T-LL (DEADBAND = 5 DEG F ADJUSTABLE)	(NO LOOPS ENABLED)							
UNOCCUPIED, MIN(ZN-T) < BLDG-T-LL (DEADBAND = 5DEG F ADJUSTABLE)	X		X	X	X		X	X
WARM-UP/COOL-DOWN	X		X	X	X	X	X	X

System will be scheduled in all modes (Basic, Adv1, Adv2)



HOT DECK VALVE CONTROL   COLD DECK VALVE CONTROL

SYSTEM: AHU-2-001, AHU-2-002
COLD DECK - HOT DECK ON/OFF SEQUENCE

F-4 Fort Bragg AHU-1 Sequence

THE CONTRACTOR SHALL PROVIDE DDC HARDWARE AND SOFTWARE TO PERFORM THIS SEQUENCE OF OPERATION AND TO PROVIDE SNVT INPUTS, OUTPUTS AND ALARM POINTS AS SPECIFIED AND SHOWN ON THE POINTS SCHEDULE DRAWING. UNLESS OTHERWISE SPECIFIED, ALL MODULATING CONTROL SHALL BE PROPORTIONAL-INTEGRAL (PI) CONTROL. THE CONTRACTOR IS RESPONSIBLE FOR PROPERLY TUNING EACH CONTROL LOOP. TUNING VALUES SHOWN ARE PROVIDED FOR INFORMATION ONLY.

THE AIR HANDLING SYSTEM SHALL ACCEPT A (BASIC, ADVANCED 1, OR ADVANCED 2) TEST MODE INPUT AS A SNVT AND SHALL OPERATE IN THE TEST MODE INDICATED BY THE TEST MODE INPUT. THE THREE TEST MODES ARE DELINEATED IN THE 'TABLE OF CONTROL LOOP OPTIONS BY TEST MODE'. THE NETWORK VARIABLE 'SYSTEM MODE' (SNVT_count_inc) SHALL BE USED TO SWITCH BETWEEN TEST MODES WHERE A VALUE OF 0 = BASIC MODE, 1 = ADVANCED MODE 1, AND 2 = ADVANCED MODE 2. CONFIGURE THE SNVT INPUT TO HAVE A DEFAULT VALUE. THE SEQUENCE MUST OPERATE IN A CONFIGURABLE DEFAULT MODE WHEN THE SNVT INPUT IS AT THE DEFAULT VALUE OR IS THE NUL VALUE. THE DDC HARDWARE SHALL BE CONFIGURED TO ROTATE THROUGH THE TEST MODES, CHANGING MODES DAILY AT MIDNIGHT.

A. HAND-OFF-AUTO SWITCHES: THE SUPPLY FAN VARIABLE FREQUENCY DRIVE (VFD) SHALL HAVE AN INTEGRAL H-O-A SWITCH:
   1. HAND: WITH THE H-O-A SWITCH IN HAND POSITION, THE SUPPLY FAN SHALL START AND RUN CONTINUOUSLY, SUBJECT TO SAFETIES, AT A MANUALLY ADJUSTABLE SPEED.
   2. OFF: WITH THE H-O-A SWITCH IN OFF POSITION, THE SUPPLY FAN SHALL STOP.
   3. AUTO: WITH THE H-O-A SWITCH IN AUTO POSITION, THE SUPPLY FAN SHALL RUN, SUBJECT TO THE SUPPLY FAN START/STOP (SF-SS) COMMAND AND SAFETIES, ACCORDING TO THE SUPPLY FAN (SPEED) COMMAND (SF-C) AND THE FAN CAPACITY CONTROL LOOP.

B. OCCUPANCY MODES: THE SYSTEM SHALL ACCEPT AN OCCUPANCY COMMAND AND OCCUPANCY OVERRIDE COMMANDS FROM THE NETWORK AS NETWORK VARIABLES OF TYPE SNVT_OCCUPANCY AND SHALL OPERATE IN ONE OF THE FOLLOWING MODES: OCCUPIED, UNOCCUPIED, OR WARMUP/COOLDOWN AS DETERMINED BY THESE NETWORK VARIABLES, WHERE:
   1. IF THE OCCUPANCY OVERRIDE INPUT IS NOT OC_NUL OR OC_BYPASS, THE SYSTEM SHALL RUN ACCORDING THE OVERRIDE INPUT ACCORDING TO THE FOLLOWING:
      i. OC_OCCUPIED: OCCUPIED MODE
      ii. OC_UNOCCUPIED: UNOCCUPIED MODE
      iii. OC_STANDBY: WARM-UP/COOLDOWN MODE
   2. IF THE OCCUPANCY OVERRIDE IS OC_NUL OR OC_BYPASS, THE SYSTEM SHALL RUN ACCORDING TO THE OCCUPANCY COMMAND INPUT ACCORDING TO THE FOLLOWING:
      i. OC_OCCUPIED: OCCUPIED MODE
      ii. OC_UNOCCUPIED: UNOCCUPIED MODE
      iii. OC_STANDBY: WARMUP/COOLDOWN MODE
      iv. OC_BYPASS: WARMUP/COOLDOWN MODE
      v. OC_NUL: OCCUPIED MODE
   3. THE BUILDING OCCUPANCY MODES SHALL BE SET VIA THE LOCAL DISPLAY PANEL (LND-WS) USING A TIME-CLOCK SCHEDULER. THE SYSTEM SHALL BE OCCUPIED FROM 0500 TO 1800 HOURS. IN EACH OCCUPANCY MODE, THE SYSTEM SHALL OPERATE AS INDICATED IN THE "TABLE OF ENABLED LOOPS".

C. PROOFS AND SAFETIES: THE SUPPLY FAN AND ALL DDC HARDWARE CONTROL LOOPS SHALL BE SUBJECT TO PROOFS AND SAFETIES. SAFETIES SHALL BE DIRECT-HARDWIRE INTERLOCKED TO THE FAN START CIRCUIT. DDC HARDWARE SHALL MONITOR ALL PROOFS AND SAFETIES AND FAILURE OF ANY PROOF OR ACTIVATION OF ANY SAFETY SHALL RESULT IN ALL CONTROL LOOPS BEING DISABLED AND THE AHU FAN BEING COMMANDED OFF UNTIL RESET. ACTIVATION OF THE TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL) SHALL RESULT IN ENABLING OF THE HOT DECK COIL CONTROL AT A HOT DECK TEMPERATURE SETPOINT OF 75 DEG F. DDC HARDWARE RESET OF TEMPERATURE LOW LIMIT SHALL BE VIA A LOCAL PUSH-BUTTON
   1. PROOFS:
      i. SUPPLY FAN STATUS (PROOF) (SF-S)
   2. SAFETIES:
      i. TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL)
      ii. RETURN AIR SMOKE (RA-SMK)

D. FAN CAPACITY CONTROL
   1. WHEN DISABLED: WHEN THIS LOOP IS DISABLED THE FAN SHALL BE COMMANDED OFF
   2. WHEN ENABLED: FAN CAPACITY CONTROL SHALL BE EITHER CONSTANT OR VARIABLE FAN SPEED CONTROL (VBL-FAN-ENA, SHOWN IN THE CONTROL LOGIC DIAGRAM) BASED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE".
      i. CONSTANT FAN SPEED: SOFT START (RAMP) THE SUPPLY FAN SPEED COMMAND (SF-C) TO 100% AND MAINTAIN SUPPLY FAN COMMAND AT 100%.
      ii. VARIABLE FAN SPEED: AS DESCRIBED BELOW
   3. VARIABLE FAN SPEED: SOFT START (RAMP) THE SUPPLY FAN AND MODULATE THE SUPPLY FAN COMMAND (SF-C) BASED ON THE ZONE TERMINAL LOAD (TL) COMMAND (ZN-TL-C) FOR EACH ZONE. THE FAN SPEED SHALL INCREASE FROM MINIMUM SPEED TO 100% AS THE ZONE TL RISES THROUGH THE CONFIGURED TL RANGE OF 80 TO 140, USING A LINEAR RESET SCHEDULE. THE PROCESS VARIABLE FOR FAN SPEED CONTROL IS MAXIMUM TL COMMAND (ZN-TL-C-EFF) DETERMINED AS FOLLOWS AND AS SHOWN IN THE CONTROL LOGIC DIAGRAM:
      i. STEP 1: DETERMINE THE HIGHEST TL (HIGHEST COOLING LOAD: ZN-TL-MAX)
      ii. STEP 2: DETERMINE THE LOWEST TL (HIGHEST HEATING LOAD: ZN-TL-MIN)
      iii. STEP 3: USE THE GREATEST ABSOLUTE VALUE TL FROM STEP 1 AND STEP 2 AS THE PROCESS VARIABLE (ZN-TL-C-EFF) FOR THE PI CONTROL LOOP.
      iv. SUPPLY FAN SPEED SHALL NOT BE REDUCED BELOW THE CONFIGURED MINIMUM SUPPLY FAN SPEED (SF-C-MIN) OR BELOW THE FAN SPEED SET BY THE MIXED AIR TEMPERATURE LOW LIMIT SETPOINT (MA-T-LL-SP). MIXED AIR LOW LIMIT MINIMUM FAN SPEED DETERMINATION IS AS FOLLOWS: MIXED AIR LOW LIMIT MINIMUM FAN SPEED FOR SYSTEMS WITHOUT A PREHEAT COIL: USE A REVERSE ACTING PI LOOP WITH A PROCESS VARIABLE OF MA-T AND MA-T-LL-SP (48 DEGREES F) AS SETPOINT TO ESTABLISH THE MIXED AIR LOW LIMIT MINIMUM FAN SPEED. (THE PI LOOP HAS THE FOLLOWING: ACTION: REVERSE ACTING, PROCESS VARIABLE: MA-T, SETPOINT: MA-T-LL-SP, OUTPUT: THE "MIXED AIR LOW LIMIT MINIMUM FAN SPEED" USED BY THE FAN CAPACITY CONTROL LOOP.)
      v. THE FOLLOWING VALUES SHALL BE USER CONFIGURABLE AND SHALL BE CONFIGURED WITH THE FOLLOWING DEFAULT VALUES:
         1. TL RANGE: 80 TO 140
         2. CONFIGURED MINIMUM SUPPLY FAN SPEED: 35%

E. OUTSIDE AIR FLOW CONTROL
   1. WHEN DISABLED: THE OUTSIDE AIR DAMPER SHALL BE CLOSED
   2. WHEN ENABLED: CONTROL OUTSIDE AIR DAMPER AS INDICATED IN "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE" AND FOR PRE-EMPTIVE FREEZE PROTECTION:
      i. FIXED DAMPER POSITION: COMMAND THE OUTSIDE AIR (OA) DAMPER TO THE FIXED POSITION (MA-D-C-FIXED) THAT CORRESPONDS TO AN OUTSIDE AIR VOLUMETRIC FLOW (OA-F) OF 920 CFM AS SET DURING THE INITIAL TEST AND BALANCE.
      ii. CONTROL TO FIXED FLOW SETPOINT: MODULATE THE OUTSIDE AIR (OA) DAMPER TO MAINTAIN THE OA VOLUMETRIC FLOW (OA-F) AT THE FIXED OCCUPIED SETPOINT (OA-F-SP) OF 920 CFM.

iii. DEMAND CONTROL VENTILATION: THE DDC HARDWARE SHALL MODULATE THE OUTSIDE AIR (OA) DAMPER TO MAINTAIN THE OA VOLUMETRIC FLOW (OA-F) AT SETPOINT (OA-F-SP) BASED ON THE OCCUPANCY SENSED IN CLASSROOMS 133, 134, AND 135. IF NO CLASSROOMS ARE OCCUPIED AS SENSED BY THE ZONE OCCUPANCY SENSORS THEN AHU-1 OA-F-SP SHALL BE 400 CFM. IF ANY ONE OR MORE OF THE THREE CLASSROOMS ARE OCCUPIED AS SENSED BY ANY OF THE ZONE OCCUPANCY SENSORS THEN OA-F-S SHALL BE RESET TO 920 CFM.

3. PRE-EMPTIVE FREEZE PROTECTION FOR SYSTEMS WITHOUT A PRE-HEAT COIL: WHEN SUPPLY FAN COMMAND IS 100% AND THE MIXED AIR TEMPERATURE IS MORE THAN 3 DEGREES F BELOW THE MIXED AIR TEMPERATURE LOW LIMIT SETPOINT (MA-T-LL-SP), MODULATE THE OA DAMPER CLOSED USING A RESET SCHEDULE SUCH THAT THE OUTSIDE AIR DAMPER IS FULLY CLOSED AT A MIXED AIR TEMPERATURE OF 8 DEGREES F BELOW MA-T-LL-SP.

F. MIXED AIR TEMPERATURE CONTROL WITH ECONOMIZER:

1. WHEN DISABLED: ECONOMIZER SHALL BE OFF
2. WHEN ENABLED:
   i. ECONOMIZER SHALL BE ON WHEN THE COLD DECK IS ON AND THE OUTSIDE AIR DRY BULB TEMPERATURE IS BETWEEN THE HIGH LIMIT (ECO-HL-SP) AND LOW LIMIT (ECO-LL-SP) SETPOINTS AS SHOWN, WITH A 2 DEGREE F DEADBAND.
   ii. ECONOMIZER SHALL BE OFF OTHERWISE
   iii. WHEN ECONOMIZER IS ON, MODULATE THE ECONOMIZER OUTSIDE AIR, RELIEF, AND RETURN AIR DAMPERS TO MAINTAIN THE MIXED AIR TEMPERATURE (MA-T) AT SETPOINT (MA-T-SP) AS SHOWN. DAMPER COMMAND SHALL NOT DROP BELOW THAT REQUIRED TO MAINTAIN OUTSIDE AIR FLOW CONTROL.

G. HOT DECK TEMPERATURE CONTROL:

1. WHEN DISABLED: THE HOT DECK VALVE CONTROL SHALL BE OFF
2. WHEN ENABLED:
   i. HOT DECK 'VALVE CONTROL' SHALL BE ON OR OFF IN ACCORDANCE WITH THE TABLE OF CONTROL LOOP OPTIONS BY TEST MODE
      1. THE HOT DECK VALVE CONTROL SHALL BE ON WHEN ANY ZONE TL IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-TL < HTG-OO-LL). THE HOT DECK VALVE CONTROL SHALL REMAIN ON UNTIL ALL ZONE TL SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (ALL ZN-TL > HTG-OO-HL).
      2. WHEN ALL ZONE TL SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (ALL ZN-TL > HTG-OO-HL)THE HOT DECK VALVE CONTROL SHALL BE OFF ANO SHALL REMAIN OFF UNTIL ANY ZONE TL IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-TL < HTG-OO-LL)
      3. HTG-OO-LL AND HTG-OO-HL SHALL BE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:
         a. HTG-OO-LL: -15%
         b. HTG-OO-HL: -5%
   ii. WHEN HOT DECK VALVE CONTROL IS OFF: HOT DECK HEATING COIL VALVE SHALL BE CLOSED
   iii. WHEN HOT DECK VALVE CONTROL IS ON: MODULATE THE HOT DECK HEATING COIL VALVE TO MAINTAIN THE HOT DECK TEMPERATURE (HD-T) AT SETPOINT (HD-T-SP). WHEN INDICATED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE", RESET HOT DECK SETPOINT (HD-T-SP) BASED ON OUTDOOR AIR TEMPERATURE USING A RESET SCHEDULE: WHEN THE OUTDOOR AIR TEMPERATURE IS LESS THAN OR EQUAL TO 50 DEG F THEN THE HOT DECK TEMPERATURE SETPIONT SHALL BE 90 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN 50 DEGREES F AND LESS THAN 70 DEGREES F THEN THE HOT DECK TEMPERATURE SETPOINT SHALL BE 85 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN OR EQUAL TO 70 DEGREES F THEN THE HOT DECK TEMPERATURE SETPOINT SHALL BE 80 DEGREES F.

H. COLD DECK TEMPERATURE CONTROL

1. WHEN DISABLED: THE COLD DECK VALVE CONTROL SHALL BE OFF
2. WHEN ENABLED:
   i. COLD DECK 'VALVE CONTROL' SHALL BE ON OR OFF IN ACCORDANCE WITH THE TABLE OF CONTROL LOOP OPTIONS BY TEST MODE
      1. COLD DECK VALVE CONTROL SHALL BE ON WHEN ANY ZONE TL IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-TL > CLG-OO-HL). THE COLD DECK VALVE CONTROL SHALL REMAIN ON UNTIL ALL ZONE TL SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-TL < CLG-OO-LL).
      2. WHEN ALL ZONE TL SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-TL < CLG-OO-LL)THE COLD DECK VALVE CONTROL SHALL BE OFF AND SHALL REMAIN OFF UNTIL ANY ZONE TL IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-TL > CLG-OO-HL).
      3. CLG-OO-LL AND CLG-OO-HL SHALL BE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:
         a. CLG-OO-LL: 5%
         b. CLG-OO-HL: 15%
   ii. WHEN COLD DECK VALVE CONTROL IS OFF: COLD DECK COOLING COIL VALVE SHALL BE CLOSED
   iii. WHEN COLD DECK VALVE CONTROL IS ON: MODULATE THE COLD DECK COOLING COIL VALVE TO MAINTAIN THE COLD DECK TEMPERATURE (CD-T) AT SETPOINT (CD-T-SP).

I. ZONE TEMPERATURE CONTROL:

1. THE ZONE TEMPERATURE SETPOINT (ZN-T-SP) SHALL BE AT THE CONFIGURED SETPOINT.
2. THE DDC HARDWARE SHALL MODULATE THE HOT DECK AND COLD DECK DAMPERS TO MAINTAIN ZONE TEMPERATURE (ZN-T) AT SETPOINT (ZN-T-SP).
   i. UPON A RISE IN ZN-T ABOVE ZN-T-SP, THE ZONE COLD DECK DAMPER SHALL MODULATE OPEN TO THE COOLING COIL AND CLOSED TO THE BYPASS. THE HOT DECK DAMPER SHALL MODULATE CLOSED TO THE HEATING COIL AND OPEN TO THE BYPASS.
   ii. UPON A FALL IN ZONE TEMPERATURE BELOW ZONE TEMPERATURE SETPOINT THE HOT DECK DAMPER SHALL MODULATE OPEN TO THE HEATING COIL AND CLOSED TO THE BYPASS. THE COLD DECK DAMPER SHALL MODULATE CLOSED TO THE COOLING COIL AND OPEN TO THE BYPASS.

F-5 Fort Bragg AHU-2 Sequence Of Operation

THE CONTRACTOR SHALL PROVIDE DDC HARDWARE AND SOFTWARE TO PERFORM THIS SEQUENCE OF OPERATION AND TO PROVIDE SNVT INPUTS, OUTPUTS AND ALARM POINTS AS SPECIFIED AND SHOWN ON THE POINTS SCHEDULE DRAWING. UNLESS OTHERWISE SPECIFIED, ALL MODULATING CONTROL SHALL BE PROPORTIONAL-INTEGRAL (PI) CONTROL. THE CONTRACTOR IS RESPONSIBLE FOR PROPERLY TUNING EACH CONTROL LOOP. TUNING VALUES SHOWN ARE PROVIDED FOR INFORMATION ONLY.

THE AIR HANDLING SYSTEM SHALL ACCEPT A (BASIC, ADVANCED 1, OR ADVANCED 2) TEST MODE INPUT AS A SNVT AND SHALL OPERATE IN THE TEST MODE INDICATED BY THE TEST MODE INPUT. THE THREE TEST MODES ARE DELINEATED IN THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE". THE NETWORK VARIABLE "SYSTEM MODE" (SNVT_count_inc) SHALL BE USED TO SWITCH BETWEEN TEST MODES WHERE A VALUE OF 0 = BASIC MODE, 1 = ADVANCED MODE 1, AND 2 = ADVANCED MODE 2. CONFIGURE THE SNVT INPUT TO HAVE A DEFAULT VALUE. THE SEQUENCE MUST OPERATE IN A CONFIGURABLE DEFAULT MODE WHEN THE SNVT INPUT IS AT THE DEFAULT VALUE OR IS THE NUL VALUE THE DDC HARDWARE SHALL BE CONFIGURED TO ROTATE THROUGH THE TEST MODES, CHANGING MODES DAILY AT MIDNIGHT.

HAND-OFF-AUTO SWITCHES: THE SUPPLY FAN VARIABLE FREQUENCY DRIVE (VFD) SHALL HAVE AN INTEGRAL H-O-A SWITCH:

1. HAND: WITH THE H-O-A SWITCH IN HAND POSITION, THE SUPPLY FAN SHALL START AND RUN CONTINUOUSLY, SUBJECT TO SAFETIES, AT A MANUALLY ADJUSTABLE SPEED.
2. OFF: WITH THE H-O-A SWITCH IN OFF POSITION, THE SUPPLY FAN SHALL STOP.
3. AUTO: WITH THE H-O-A SWITCH IN AUTO POSITION, THE SUPPLY FAN SHALL RUN, SUBJECT TO THE SUPPLY FAN START/STOP (SF-SS) COMMAND AND SAFETIES, ACCORDING TO THE SUPPLY FAN (SPEED) COMMAND (SF-C) AND THE FAN CAPACITY CONTROL LOOP.

B. OCCUPANCY MODES: THE SYSTEM SHALL ACCEPT AN OCCUPANCY COMMAND AND OCCUPANCY OVERRIDE COMMANDS FROM THE NETWORK AS NETWORK VARIABLES OF TYPE SNVT_OCCUPANCY AND SHALL OPERATE IN ONE OF THE FOLLOWING MODES: OCCUPIED, UNOCCUPIED, OR WARMUP/COOLDOWN AS DETERMINED BY THESE NETWORK VARIABLES, WHERE:

1. IF THE OCCUPANCY OVERRIDE INPUT IS NOT OC_NUL OR OC_BYPASS, THE SYSTEM SHALL RUN ACCORDING THE OVERRIDE INPUT ACCORDING TO THE FOLLOWING:
   - i. OC_OCCUPIED: OCCUPIED MODE
   - ii. OC_UNOCCUPIED: UNOCCUPIED MODE
   - iii. OC_STANDBY: WARM-UP/COOLDOWN MODE
2. IF THE OCCUPANCY OVERRIDE IS OC_NUL OR OC_BYPASS, THE SYSTEM SHALL RUN ACCORDING TO THE OCCUPANCY COMMAND INPUT ACCORDING TO THE FOLLOWING:
   - i. OC_OCCUPIED: OCCUPIED MODE
   - ii. OC_UNOCCUPIED: UNOCCUPIED MODE
   - iii. OC_STANDBY: WARMUP/COOLDOWN MODE
   - iv. OC_BYPASS: WARMUP/COOLDOWN MODE
   - v. OC_NUL: OCCUPIED MODE
3. THE BUILDING OCCUPANCY MODES SHALL BE SET VIA THE LOCAL DISPLAY PANEL (LND-WS) USING A TIME-CLOCK SCHEDULER. THE SYSTEM SHALL BE OCCUPIED FROM 0500 TO 1800 HOURS. IN EACH OCCUPANCY MODE, THE SYSTEM SHALL OPERATE AS INDICATED IN THE "TABLE OF ENABLED LOOPS".

C. PROOFS AND SAFETIES: THE SUPPLY FAN AND ALL DDC HARDWARE CONTROL LOOPS SHALL BE SUBJECT TO PROOFS AND SAFETIES. SAFETIES SHALL BE DIRECT-HARDWIRE INTERLOCKED TO THE FAN START CIRCUIT. DDC HARDWARE SHALL MONITOR ALL PROOFS AND SAFETIES AND FAILURE OF ANY PROOF OR ACTIVATION OF ANY SAFETY SHALL RESULT IN ALL CONTROL LOOPS BEING DISABLED AND THE AHU FAN BEING COMMANDED OFF UNTIL RESET. ACTIVATION OF THE TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL) SHALL RESULT IN ENABLING OF THE HOT DECK COIL CONTROL AT A HOT DECK TEMPERATURE SETPOINT OF 75 DEG F. DDC HARDWARE RESET OF TEMPERATURE LOW LIMIT SHALL BE VIA A LOCAL PUSH-BUTTON

1. PROOFS:
   - i. SUPPLY FAN STATUS (PROOF) (SF-S)
2. SAFETIES:
   - i. TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL)
   - ii. RETURN AIR SMOKE (RA-SMK)

D. FAN CAPACITY CONTROL

1. WHEN DISABLED: WHEN THIS LOOP IS DISABLED THE FAN SHALL BE COMMANDED OFF
2. WHEN ENABLED: FAN CAPACITY CONTROL SHALL BE EITHER CONSTANT OR VARIABLE FAN SPEED CONTROL (VBL-FAN-ENA, SHOWN IN THE CONTROL LOGIC DIAGRAM) BASED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE".
   - i. CONSTANT FAN SPEED: SOFT START (RAMP) THE SUPPLY FAN SPEED COMMAND (SF-C) TO 100% AND MAINTAIN SUPPLY FAN COMMAND AT 100%.
   - ii. VARIABLE FAN SPEED: AS DESCRIBED BELOW
3. VARIABLE FAN SPEED: SOFT START (RAMP) THE SUPPLY FAN AND MODULATE THE SUPPLY FAN COMMAND (SF-C) BASED ON THE ZONE TERMINAL LOAD (TL) COMMAND (ZN-TL-C) FOR EACH ZONE. THE FAN SPEED SHALL INCREASE FROM MINIMUM SPEED TO 100% AS THE ZONE TL RISES THROUGH THE CONFIGURED TL RANGE OF 80 TO 140, USING A LINEAR RESET SCHEDULE. THE PROCESS VARIABLE FOR FAN SPEED CONTROL IS MAXIMUM TL COMMAND (ZN-TL-C-EFF) DETERMINED AS FOLLOWS AND AS SHOWN IN THE CONTROL LOGIC DIAGRAM:
   - i. STEP 1: DETERMINE THE HIGHEST TL (HIGHEST COOLING LOAD: ZN-TL-MAX)
   - ii. STEP 2: DETERMINE THE LOWEST TL (HIGHEST HEATING LOAD: ZN-TL-MIN)
   - iii. STEP 3: USE THE GREATEST ABSOLUTE VALUE TL FROM STEP 1 AND STEP 2 AS THE PROCESS VARIABLE (ZN-TL-C-EFF) FOR THE PI CONTROL LOOP.
   - iv. SUPPLY FAN SPEED SHALL NOT BE REDUCED BELOW THE CONFIGURED MINIMUM SUPPLY FAN SPEED (SF-C-MIN) OR BELOW THE FAN SPEED SET BY THE MIXED AIR TEMPERATURE LOW LIMIT SETPOINT (MA-T-LL-SP). MIXED AIR LOW LIMIT MINIMUM FAN SPEED DETERMINATION IS AS FOLLOWS: MIXED AIR LOW LIMIT MINIMUM FAN SPEED FOR SYSTEMS WITHOUT A PREHEAT COIL: USE A REVERSE ACTING PI LOOP WITH A PROCESS VARIABLE OF MA-T AND MA-T-LL-SP (48 DEGREES F) AS SETPOINT TO ESTABLISH THE MIXED AIR LOW LIMIT MINIMUM FAN SPEED. (THE PI LOOP HAS THE FOLLOWING: ACTION: REVERSE ACTING, PROCESS VARIABLE: MA-T, SETPOINT: MA-T-LL-SP, OUTPUT: THE "MIXED AIR LOW LIMIT MINIMUM FAN SPEED" USED BY THE FAN CAPACITY CONTROL LOOP.)
   - v. THE FOLLOWING VALUES SHALL BE USER CONFIGURABLE AND SHALL BE CONFIGURED WITH THE FOLLOWING DEFAULT VALUES:
     1. TL RANGE: 80 TO 140
     2. CONFIGURED MINIMUM SUPPLY FAN SPEED: 35%

E. OUTSIDE AIR FLOW CONTROL

1. WHEN DISABLED: THE OUTSIDE AIR DAMPER SHALL BE CLOSED
2. WHEN ENABLED: CONTROL OUTSIDE AIR DAMPER AS INDICATED IN "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE" AND FOR PRE-EMPTIVE FREEZE PROTECTION:
   - i. FIXED DAMPER POSITION: COMMAND THE OUTSIDE AIR (OA) DAMPER TO THE FIXED POSITION (MA-D-C-FIXED) THAT CORRESPONDS TO AN OUTSIDE AIR VOLUMETRIC FLOW (OA-F) OF 720 CFM AS SET DURING THE INITIAL TEST AND BALANCE.
   - ii. CONTROL TO FIXED FLOW SETPOINT: MODULATE THE OUTSIDE AIR (OA) DAMPER TO MAINTAIN THE OA VOLUMETRIC FLOW (OA-F) AT THE FIXED OCCUPIED SETPOINT (OA-F-SP) OF 720 CFM.

3. PRE-EMPTIVE FREEZE PROTECTION FOR SYSTEMS WITHOUT A PRE-HEAT COIL: WHEN SUPPLY FAN COMMAND IS 100% AND THE MIXED AIR TEMPERATURE IS MORE THAN 3 DEGREES F BELOW THE MIXED AIR TEMPERATURE LOW LIMIT SETPOINT (MA-T-LL-SP), MODULATE THE OA DAMPER CLOSED USING A RESET SCHEDULE SUCH THAT THE OUTSIDE AIR DAMPER IS FULLY CLOSED AT A MIXED AIR TEMPERATURE OF 8 DEGREES F BELOW MA-T-LL-SP.

F. MIXED AIR TEMPERATURE CONTROL WITH ECONOMIZER:

1. WHEN DISABLED: ECONOMIZER SHALL BE OFF

2. WHEN ENABLED:

i. ECONOMIZER SHALL BE ON WHEN THE COLD DECK IS ON AND THE OUTSIDE AIR DRY BULB TEMPERATURE IS BETWEEN THE HIGH LIMIT (ECO-HL-SP) AND LOW LIMIT (ECO-LL-SP) SETPOINTS AS SHOWN, WITH A 2 DEGREE F DEADBAND.

ii. ECONOMIZER SHALL BE OFF OTHERWISE

iii. WHEN ECONOMIZER IS ON, MODULATE THE ECONOMIZER OUTSIDE AIR, RELIEF, AND RETURN AIR DAMPERS TO MAINTAIN THE MIXED AIR TEMPERATURE (MA-T) AT SETPOINT (MA-T-SP) AS SHOWN. DAMPER COMMAND SHALL NOT DROP BELOW THAT REQUIRED TO MAINTAIN OUTSIDE AIR FLOW CONTROL.

G. HOT DECK TEMPERATURE CONTROL:

1. WHEN DISABLED: THE HOT DECK VALVE CONTROL SHALL BE OFF

2. WHEN ENABLED:

i. HOT DECK 'VALVE CONTROL' SHALL BE ON OR OFF IN ACCORDANCE WITH THE TABLE OF CONTROL LOOP OPTIONS BY TEST MODE

1. THE HOT DECK VALVE CONTROL SHALL BE ON WHEN ANY ZONE TL IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-TL < HTG-OO-LL). THE HOT DECK VALVE CONTROL SHALL REMAIN ON UNTIL ALL ZONE TL SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (ALL ZN-TL > HTG-OO-HL).

2. WHEN ALL ZONE TL SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (ALL ZN-TL > HTG-OO-HL)THE HOT DECK VALVE CONTROL SHALL BE OFF ANO SHALL REMAIN OFF UNTIL ANY ZONE TL IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-TL < HTG-OO-LL)

3. HTG-OO-LL AND HTG-OO-HL SHALL BE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:

a. HTG-OO-LL: -15%

b. HTG-OO-HL: -5%

ii. WHEN HOT DECK VALVE CONTROL IS OFF: HOT DECK HEATING COIL VALVE SHALL BE CLOSED

iii. WHEN HOT DECK VALVE CONTROL IS ON: MODULATE THE HOT DECK HEATING COIL VALVE TO MAINTAIN THE HOT DECK TEMPERATURE (HD-T) AT SETPOINT (HD-T-SP). WHEN INDICATED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE", RESET HOT DECK SETPOINT (HD-T-SP) BASED ON OUTDOOR AIR TEMPERATURE USING A RESET SCHEDULE: WHEN THE OUTDOOR AIR TEMPERATURE IS LESS THAN OR EQUAL TO 50 DEG F THEN THE HOT DECK TEMPERATURE SETPIONT SHALL BE 90 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN 50 DEGREES F AND LESS THAN 70 DEGREES F THEN THE HOT DECK TEMPERATURE SETPOINT SHALL BE 85 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN OR EQUAL TO 70 DEGREES F THEN THE HOT DECK TEMPERATURE SETPOINT SHALL BE 80 DEGREES F.

H. COLD DECK TEMPERATURE CONTROL

1. WHEN DISABLED: THE COLD DECK VALVE CONTROL SHALL BE OFF

2. WHEN ENABLED:

i. COLD DECK 'VALVE CONTROL' SHALL BE ON OR OFF IN ACCORDANCE WITH THE TABLE OF CONTROL LOOP OPTIONS BY TEST MODE

1. COLD DECK VALVE CONTROL SHALL BE ON WHEN ANY ZONE TL IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-TL > CLG-OO-HL). THE COLD DECK VALVE CONTROL SHALL REMAIN ON UNTIL ALL ZONE TL SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-TL < CLG-OO-LL).

2. WHEN ALL ZONE TL SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-TL < CLG-OO-LL)THE COLD DECK VALVE CONTROL SHALL BE OFF AND SHALL REMAIN OFF UNTIL ANY ZONE TL IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-TL > CLG-OO-HL).

3. CLG-OO-LL AND CLG-OO-HL SHALL BE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:

a. CLG-OO-LL: 5%

b. CLG-OO-HL: 15%

ii. WHEN COLD DECK VALVE CONTROL IS OFF: COLD DECK COOLING COIL VALVE SHALL BE CLOSED

iii. WHEN COLD DECK VALVE CONTROL IS ON: MODULATE THE COLD DECK COOLING COIL VALVE TO MAINTAIN THE COLD DECK TEMPERATURE (CD-T) AT SETPOINT (CD-T-SP).

I. ZONE TEMPERATURE CONTROL:

1. THE ZONE TEMPERATURE SETPOINT (ZN-T-SP) SHALL BE AT THE CONFIGURED SETPOINT.

2. THE DDC HARDWARE SHALL MODULATE THE HOT DECK AND COLD DECK DAMPERS TO MAINTAIN ZONE TEMPERATURE (ZN-T) AT SETPOINT (ZN-T-SP).

i. UPON A RISE IN ZN-T ABOVE ZN-T-SP, THE ZONE COLD DECK DAMPER SHALL MODULATE OPEN TO THE COOLING COIL AND CLOSED TO THE BYPASS. THE HOT DECK DAMPER SHALL MODULATE CLOSED TO THE HEATING COIL AND OPEN TO THE BYPASS.

ii. UPON A FALL IN ZONE TEMPERATURE BELOW ZONE TEMPERATURE SETPOINT THE HOT DECK DAMPER SHALL MODULATE OPEN TO THE HEATING COIL AND CLOSED TO THE BYPASS. THE COLD DECK DAMPER SHALL MODULATE CLOSED TO THE COOLING COIL AND OPEN TO THE BYPASS.

J. GENERAL EXHAUST FAN (FOR BUILDING AND BATHROOMS) SEQUENCE OF OPERATIONS:

1. OCCUPIED MODE: EXHAUST FAN EF-3 SHALL BE COMMANDED TO RUN (EF-3-SS) AND THE ASSOCIATED DAMPER ACTUATOR SHALL BE COMMANDED OPEN (EF-3-DA-C).

2. UNOCCUPIED MODE: EXHAUST FAN EF-3 SHALL BE OFF AND THE ASSOCIATED DAMPER ACTUATOR SHALL BE COMMANDED CLOSED.

K. MECHANICAL ROOM VENTILATION SEQUENCE OF OPERATIONS:

1. TEMPERATURE CONTROL: WHEN THE MECHANICAL ROOM TEMPERATURE AS SENSED BY THE MECHANICAL ROOM TEMPERATURE SENSOR IS ABOVE SETPOINT, FAN F-4 SHALL BE ENERGIZED (F-4-SS) AND FAN F-4 INTAKE/GENERAL RELIEF AIR DAMPER SHALL OPEN.

2. PRESSURE CONTROL: THE TWO F-4 INTAKE/GENERAL RELIEF AIR DAMPERS SHALL BE COMMANDED OPEN WHENEVER THE AHU-1, 2, OR 3 RELIEF DAMPERS OPEN.

F-6 Fort Bragg AHU-3 Sequence

THE CONTRACTOR SHALL PROVIDE DDC HARDWARE AND SOFTWARE TO PERFORM THIS SEQUENCE OF OPERATION AND TO PROVIDE SNVT INPUTS, OUTPUTS AND ALARM POINTS AS SPECIFIED AND SHOWN ON THE POINTS SCHEDULE DRAWING. UNLESS OTHERWISE SPECIFIED, ALL MODULATING CONTROL SHALL BE PROPORTIONAL-INTEGRAL (PI) CONTROL. THE CONTRACTOR IS RESPONSIBLE FOR PROPERLY TUNING EACH CONTROL LOOP. TUNING VALUES SHOWN ARE PROVIDED FOR INFORMATION ONLY.

THE AIR HANDLING SYSTEM SHALL ACCEPT A (BASIC, ADVANCED 1, OR ADVANCED 2) TEST MODE INPUT AS A SNVT AND SHALL OPERATE IN THE TEST MODE INDICATED BY THE TEST MODE INPUT. THE THREE TEST MODES ARE DELINEATED IN THE 'TABLE OF CONTROL LOOP OPTIONS BY TEST MODE'. THE NETWORK VARIABLE 'SYSTEM MODE' (SNVT_count_inc) SHALL BE USED TO SWITCH BETWEEN TEST MODES WHERE A VALUE OF 0 = BASIC MODE, 1 = ADVANCED MODE 1, AND 2 = ADVANCED MODE 2. CONFIGURE THE SNVT INPUT TO HAVE A DEFAULT VALUE. THE SEQUENCE MUST OPERATE IN A CONFIGURABLE DEFAULT MODE WHEN THE SNVT INPUT IS AT THE DEFAULT VALUE OR IS THE NUL VALUE. THE DDC HARDWARE SHALL BE CONFIGURED TO ROTATE THROUGH THE TEST MODES, CHANGING MODES DAILY AT MIDNIGHT

A. HAND-OFF-AUTO SWITCHES: THE SUPPLY FAN VARIABLE FREQUENCY DRIVE (VFD) SHALL HAVE AN INTEGRAL H-O-A SWITCH:
   1. HAND: WITH THE H-O-A SWITCH IN HAND POSITION, THE SUPPLY FAN SHALL START AND RUN CONTINUOUSLY, SUBJECT TO SAFETIES, AT A MANUALLY ADJUSTABLE SPEED.
   2. OFF: WITH THE H-O-A SWITCH IN OFF POSITION, THE SUPPLY FAN SHALL STOP.
   3. AUTO: WITH THE H-O-A SWITCH IN AUTO POSITION, THE SUPPLY FAN SHALL RUN, SUBJECT TO THE SUPPLY FAN START/STOP (SF-SS) COMMAND AND SAFETIES, ACCORDING TO THE SUPPLY FAN (SPEED) COMMAND (SF-C) AND THE FAN CAPACITY CONTROL LOOP.

B. OCCUPANCY MODES: THE SYSTEM SHALL ACCEPT AN OCCUPANCY COMMAND AND OCCUPANCY OVERRIDE COMMANDS FROM THE NETWORK AS NETWORK VARIABLES OF TYPE SNVT_OCCUPANCY AND SHALL OPERATE IN ONE OF THE FOLLOWING MODES: OCCUPIED, UNOCCUPIED, OR WARMUP/COOLDOWN AS DETERMINED BY THESE NETWORK VARIABLES, WHERE:
   1. IF THE OCCUPANCY OVERRIDE INPUT IS NOT OC_NUL OR OC_BYPASS, THE SYSTEM SHALL RUN ACCORDING THE OVERRIDE INPUT ACCORDING TO THE FOLLOWING:
      i. OC_OCCUPIED: OCCUPIED MODE
      ii. OC_UNOCCUPIED: UNOCCUPIED MODE
      iii. OC_STANDBY: WARM-UP/COOLDOWN MODE
   2. IF THE OCCUPANCY OVERRIDE IS OC_NUL OR OC_BYPASS, THE SYSTEM SHALL RUN ACCORDING TO THE OCCUPANCY COMMAND INPUT ACCORDING TO THE FOLLOWING:
      i. OC_OCCUPIED: OCCUPIED MODE
      ii. OC_UNOCCUPIED: UNOCCUPIED MODE
      iii. OC_STANDBY: WARMUP/COOLDOWN MODE
      iv. OC_BYPASS: WARMUP/COOLDOWN MODE
      v. OC_NUL: OCCUPIED MODE
   3. THE BUILDING OCCUPANCY MODES SHALL BE SET VIA THE LOCAL DISPLAY PANEL (LND-WS) USING A TIME-CLOCK SCHEDULER. THE SYSTEM SHALL BE OCCUPIED FROM 0500 TO 1800 HOURS. IN EACH OCCUPANCY MODE, THE SYSTEM SHALL OPERATE AS INDICATED IN THE "TABLE OF ENABLED LOOPS".

C. PROOFS AND SAFETIES: THE SUPPLY FAN AND ALL DDC HARDWARE CONTROL LOOPS SHALL BE SUBJECT TO PROOFS AND SAFETIES. SAFETIES SHALL BE DIRECT-HARDWIRE INTERLOCKED TO THE FAN START CIRCUIT. DDC HARDWARE SHALL MONITOR ALL PROOFS AND SAFETIES AND FAILURE OF ANY PROOF OR ACTIVATION OF ANY SAFETY SHALL RESULT IN ALL CONTROL LOOPS BEING DISABLED AND THE AHU FAN BEING COMMANDED OFF UNTIL RESET. ACTIVATION OF THE TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL) SHALL RESULT IN ENABLING OF THE HOT DECK COIL CONTROL AT A HOT DECK TEMPERATURE SETPOINT OF 75 DEG F. DDC HARDWARE RESET OF TEMPERATURE LOW LIMIT SHALL BE VIA A LOCAL PUSH-BUTTON
   1. PROOFS:
      i. SUPPLY FAN STATUS (PROOF) (SF-S)
   2. SAFETIES:
      i. TEMPERATURE LOW LIMIT (FREEZE STAT) (T-LL)
      ii. RETURN AIR SMOKE (RA-SMK)

D. FAN CAPACITY CONTROL
   1. WHEN DISABLED: WHEN THIS LOOP IS DISABLED THE FAN SHALL BE COMMANDED OFF
   2. WHEN ENABLED: FAN CAPACITY CONTROL SHALL BE EITHER CONSTANT OR VARIABLE FAN SPEED CONTROL (VBL-FAN-ENA, SHOWN IN THE CONTROL LOGIC DIAGRAM) BASED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE".
      i. CONSTANT FAN SPEED: SOFT START (RAMP) THE SUPPLY FAN SPEED COMMAND (SF-C) TO 100% AND MAINTAIN SUPPLY FAN COMMAND AT 100%.
      ii. VARIABLE FAN SPEED: AS DESCRIBED BELOW
   3. VARIABLE FAN SPEED: SOFT START (RAMP) THE SUPPLY FAN AND MODULATE THE SUPPLY FAN COMMAND (SF-C) BASED ON THE ZONE TERMINAL LOAD (TL) COMMAND (ZN-TL-C) FOR EACH ZONE. THE FAN SPEED SHALL INCREASE FROM MINIMUM SPEED TO 100% AS THE ZONE TL RISES THROUGH THE CONFIGURED TL RANGE OF 80 TO 140, USING A LINEAR RESET SCHEDULE. THE PROCESS VARIABLE FOR FAN SPEED CONTROL IS MAXIMUM TL COMMAND (ZN-TL-C-EFF) DETERMINED AS FOLLOWS AND AS SHOWN IN THE CONTROL LOGIC DIAGRAM:
      i. STEP 1: DETERMINE THE HIGHEST TL (HIGHEST COOLING LOAD: ZN-TL-MAX)
      ii. STEP 2: DETERMINE THE LOWEST TL (HIGHEST HEATING LOAD: ZN-TL-MIN)
      iii. STEP 3: USE THE GREATEST ABSOLUTE VALUE TL FROM STEP 1 AND STEP 2 AS THE PROCESS VARIABLE (ZN-TL-C-EFF) FOR THE PI CONTROL LOOP.
      iv. SUPPLY FAN SPEED SHALL NOT BE REDUCED BELOW THE CONFIGURED MINIMUM SUPPLY FAN SPEED (SF-C-MIN) OR BELOW THE FAN SPEED SET BY THE MIXED AIR TEMPERATURE LOW LIMIT SETPOINT (MA-T-LL-SP). MIXED AIR LOW LIMIT MINIMUM FAN SPEED DETERMINATION IS AS FOLLOWS: MIXED AIR LOW LIMIT MINIMUM FAN SPEED FOR SYSTEMS WITHOUT A PREHEAT COIL: USE A REVERSE ACTING PI LOOP WITH A PROCESS VARIABLE OF MA-T AND MA-T-LL-SP (48 DEGREES F) AS SETPOINT TO ESTABLISH THE MIXED AIR LOW LIMIT MINIMUM FAN SPEED. (THE PI LOOP HAS THE FOLLOWING: ACTION: REVERSE ACTING, PROCESS VARIABLE: MA-T, SETPOINT: MA-T-LL-SP, OUTPUT: THE "MIXED AIR LOW LIMIT MINIMUM FAN SPEED" USED BY THE FAN CAPACITY CONTROL LOOP.)
      v. THE FOLLOWING VALUES SHALL BE USER CONFIGURABLE AND SHALL BE CONFIGURED WITH THE FOLLOWING DEFAULT VALUES:
         1. TL RANGE: 80 TO 140
         2. CONFIGURED MINIMUM SUPPLY FAN SPEED: 35%

E. OUTSIDE AIR FLOW CONTROL
   1. WHEN DISABLED: THE OUTSIDE AIR DAMPER SHALL BE CLOSED
   2. WHEN ENABLED: CONTROL OUTSIDE AIR DAMPER AS INDICATED IN "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE" AND FOR PRE-EMPTIVE FREEZE PROTECTION:
      i. FIXED DAMPER POSITION: COMMAND THE OUTSIDE AIR (OA) DAMPER TO THE FIXED POSITION (MA-D-C-FIXED) THAT CORRESPONDS TO AN OUTSIDE AIR VOLUMETRIC FLOW (OA-F) OF 1,020 CFM AS SET DURING THE INITIAL TEST AND BALANCE.
      ii. CONTROL TO FIXED FLOW SETPOINT: MODULATE THE OUTSIDE AIR (OA) DAMPER TO MAINTAIN THE OA VOLUMETRIC FLOW (OA-F) AT THE FIXED OCCUPIED SETPOINT (OA-F-SP) OF 1,020 CFM.

iii. DEMAND CONTROL VENTILATION: THE DDC HARDWARE SHALL MODULATE THE OUTSIDE AIR (OA) DAMPER TO MAINTAIN THE OA VOLUMETRIC FLOW (OA-F) AT SETPOINT (OA-F-SP) BASED ON THE OCCUPANCY SENSED IN CONFERENCE ROOM 224. IF CONFERENCE ROOM 224 IS NOT OCCUPIED AS SENSED BY THE ZONE OCCUPANCY SENSOR THEN AHU-3 OA-F-SP SHALL BE 875 CFM. IF CONFERENCE ROOM 224 IS OCCUPIED AS SENSED BY THE ZONE OCCUPANCY SENSOR THEN OA-F-S SHALL BE RESET TO 1,020 CFM.

3. PRE-EMPTIVE FREEZE PROTECTION FOR SYSTEMS WITHOUT A PRE-HEAT COIL: WHEN SUPPLY FAN COMMAND IS 100% AND THE MIXED AIR TEMPERATURE IS MORE THAN 3 DEGREES F BELOW THE MIXED AIR TEMPERATURE LOW LIMIT SETPOINT (MA-T-LL-SP), MODULATE THE OA DAMPER CLOSED USING A RESET SCHEDULE SUCH THAT THE OUTSIDE AIR DAMPER IS FULLY CLOSED AT A MIXED AIR TEMPERATURE OF 8 DEGREES F BELOW MA-T-LL-SP.

F. MIXED AIR TEMPERATURE CONTROL WITH ECONOMIZER:

1. WHEN DISABLED: ECONOMIZER SHALL BE OFF
2. WHEN ENABLED:
   i. ECONOMIZER SHALL BE ON WHEN THE COLD DECK IS ON AND THE OUTSIDE AIR DRY BULB TEMPERATURE IS BETWEEN THE HIGH LIMIT (ECO-HL-SP) AND LOW LIMIT (ECO-LL-SP) SETPOINTS AS SHOWN, WITH A 2 DEGREE F DEADBAND.
   ii. ECONOMIZER SHALL BE OFF OTHERWISE
   iii. WHEN ECONOMIZER IS ON, MODULATE THE ECONOMIZER OUTSIDE AIR, RELIEF, AND RETURN AIR DAMPERS TO MAINTAIN THE MIXED AIR TEMPERATURE (MA-T) AT SETPOINT (MA-T-SP) AS SHOWN. DAMPER COMMAND SHALL NOT DROP BELOW THAT REQUIRED TO MAINTAIN OUTSIDE AIR FLOW CONTROL.

G. HOT DECK TEMPERATURE CONTROL:

1. WHEN DISABLED: THE HOT DECK VALVE CONTROL SHALL BE OFF
2. WHEN ENABLED:
   i. HOT DECK 'VALVE CONTROL' SHALL BE ON OR OFF IN ACCORDANCE WITH THE TABLE OF CONTROL LOOP OPTIONS BY TEST MODE
      1. THE HOT DECK VALVE CONTROL SHALL BE ON WHEN ANY ZONE TL IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-TL < HTG-OO-LL). THE HOT DECK VALVE CONTROL SHALL REMAIN ON UNTIL ALL ZONE TL SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (ALL ZN-TL > HTG-OO-HL).
      2. WHEN ALL ZONE TL SIGNALS ARE GREATER THAN THE HEATING ON/OFF HIGH LIMIT (ALL ZN-TL > HTG-OO-HL)THE HOT DECK VALVE CONTROL SHALL BE OFF ANO SHALL REMAIN OFF UNTIL ANY ZONE TL IS LESS THAN THE HEATING ON/OFF LOW LIMIT (ANY ZN-TL < HTG-OO-LL)
      3. HTG-OO-LL AND HTG-OO-HL SHALL BE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:
         a. HTG-OO-LL: -15%
         b. HTG-OO-HL: -5%
   ii. WHEN HOT DECK VALVE CONTROL IS OFF: HOT DECK HEATING COIL VALVE SHALL BE CLOSED
   iii. WHEN HOT DECK VALVE CONTROL IS ON: MODULATE THE HOT DECK HEATING COIL VALVE TO MAINTAIN THE HOT DECK TEMPERATURE (HD-T) AT SETPOINT (HD-T-SP). WHEN INDICATED ON THE "TABLE OF CONTROL LOOP OPTIONS BY TEST MODE", RESET HOT DECK SETPOINT (HD-T-SP) BASED ON OUTDOOR AIR TEMPERATURE USING A RESET SCHEDULE: WHEN THE OUTDOOR AIR TEMPERATURE IS LESS THAN OR EQUAL TO 50 DEG F THEN THE HOT DECK TEMPERATURE SETPIONT SHALL BE 90 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN 50 DEGREES F AND LESS THAN 70 DEGREES F THEN THE HOT DECK TEMPERATURE SETPOINT SHALL BE 85 DEGREES F. WHEN THE OUTDOOR AIR TEMPERATURE IS GREATER THAN OR EQUAL TO 70 DEGREES F THEN THE HOT DECK TEMPERATURE SETPOINT SHALL BE 80 DEGREES F.

H. COLD DECK TEMPERATURE CONTROL

1. WHEN DISABLED: THE COLD DECK VALVE CONTROL SHALL BE OFF
2. WHEN ENABLED:
   i. COLD DECK 'VALVE CONTROL' SHALL BE ON OR OFF IN ACCORDANCE WITH THE TABLE OF CONTROL LOOP OPTIONS BY TEST MODE
      1. COLD DECK VALVE CONTROL SHALL BE ON WHEN ANY ZONE TL IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-TL > CLG-OO-HL). THE COLD DECK VALVE CONTROL SHALL REMAIN ON UNTIL ALL ZONE TL SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-TL < CLG-OO-LL).
      2. WHEN ALL ZONE TL SIGNALS ARE LESS THAN THE COOLING ON/OFF LOW LIMIT (ALL ZN-TL < CLG-OO-LL)THE COLD DECK VALVE CONTROL SHALL BE OFF AND SHALL REMAIN OFF UNTIL ANY ZONE TL IS GREATER THAN THE COOLING ON/OFF HIGH LIMIT (ANY ZN-TL > CLG-OO-HL).
      3. CLG-OO-LL AND CLG-OO-HL SHALL BE CONFIGURABLE WITH THE FOLLOWING INITIAL VALUES:
         a. CLG-OO-LL: 5%
         b. CLG-OO-HL: 15%
   ii. WHEN COLD DECK VALVE CONTROL IS OFF: COLD DECK COOLING COIL VALVE SHALL BE CLOSED
   iii. WHEN COLD DECK VALVE CONTROL IS ON: MODULATE THE COLD DECK COOLING COIL VALVE TO MAINTAIN THE COLD DECK TEMPERATURE (CD-T) AT SETPOINT (CD-T-SP).

I. ZONE TEMPERATURE CONTROL:

1. THE ZONE TEMPERATURE SETPOINT (ZN-T-SP) SHALL BE AT THE CONFIGURED SETPOINT.
2. THE DDC HARDWARE SHALL MODULATE THE HOT DECK AND COLD DECK DAMPERS TO MAINTAIN ZONE TEMPERATURE (ZN-T) AT SETPOINT (ZN-T-SP).
   i. UPON A RISE IN ZN-T ABOVE ZN-T-SP, THE ZONE COLD DECK DAMPER SHALL MODULATE OPEN TO THE COOLING COIL AND CLOSED TO THE BYPASS. THE HOT DECK DAMPER SHALL MODULATE CLOSED TO THE HEATING COIL AND OPEN TO THE BYPASS.
   ii. UPON A FALL IN ZONE TEMPERATURE BELOW ZONE TEMPERATURE SETPOINT THE HOT DECK DAMPER SHALL MODULATE OPEN TO THE HEATING COIL AND CLOSED TO THE BYPASS. THE COLD DECK DAMPER SHALL MODULATE CLOSED TO THE COOLING COIL AND OPEN TO THE BYPASS.

J. MECHANICAL ROOM VENTILATION SEQUENCE OF OPERATIONS:

1. PRESSURE CONTROL: F-4 INTAKE/GENERAL RELIEF AIR DAMPERS SHALL BE COMMANDED OPEN WHENEVER THE AHU-1, 2, AND 3 RELIEF DAMPERS OPEN OR F-4 IS COMMANDED ON.

APPENDIX G DESIGN GUIDE

This appendix contains a design guide for use in implementing the variable volume retrofit. The template drawings referred to in the design guide are available from the points of contact in Appendix A.

DESIGN GUIDE

Multizone to Variable Air Volume Control Conversion Standard Design Package

Draft – Sept 2016

MULTIZONE TO VARIABLE AIR VOLUME CONTROL CONVERSION STANDARD DESIGN PACKAGE DESIGNER GUIDE

Sept 2016

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Task 7 – Standard Control System Design Package

Record of Changes (changes are indicated by **1**\ ... /**1**/)

Change No.	Date	Location

Contents

1 BACKGROUND

The Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) conducted a demonstration project (November 2012 – October 2015) for a technique to convert a constant volume MZ (CV-MZ) system into a variable volume MZ (VV-MZ) system by focusing almost entirely on instrumentation and controls rather than the demolition and installation of ductwork and terminal units. The approach includes upgrading the heating, ventilating, and air conditioning (HVAC) controls via programming changes or controller replacement and the installation of new and replacement actuators and sensors needed to support the conversion and to provide for monitoring and control of the system.

The technique also calls for installing a variable frequency drive (VFD) to allow for fan capacity control where, as with any variable volume system, the ability to operate the fan at reduced speed provides energy savings. Fan operation is automatically adjusted based on the position of the zone dampers where fan speed is decreased until one of the (multiple) zone dampers is at full or near full open position. The retrofit might require the replacement of the constant speed motor with an inverter compatible (or high efficiency) motor.

The technique also includes avoiding or minimizing the inefficiency of simultaneous heating and cooling inherent to conventional MZ systems. Through the use of the variable speed fan and, in some applications, control logic to modify the hot (and possibly cold) deck discharge air temperatures via a setpoint reset algorithm, the amount of energy wasted through simultaneous heating and cooling can be reduced. Further energy savings are possible through control of outdoor air quantity and demand controlled ventilation.

The work included development of a Standard Control System Design template for conversion of a MZ to a VV MZ system based on the techniques discussed above. The Standard template consists of design drawings and a guide specification (included in the design drawings) that includes the control system retrofit requirements. Also included is a narrative guide containing options typical to a project of this nature which include designer notes to describe each option. The guide shall include front-matter descriptive notes describing the basic specification approach and considerations.

2 BASIC SYSTEM CONFIGURATIONS

Multi-zone systems supply several zones from a single centrally located air handling unit. Different zone requirements are met by mixing cold, warm or bypass air through zone dampers at the air handling unit in response to zone thermostats. The mixed air is distributed throughout the building by single-zone ductwork. Multi-zone units fall into three distinct categories (this discussion assumes an air handler with mixing box capable of economizer function without a return or exhaust fan).

2.1 Hot Deck / Cold Deck (Standard multizone)

Return air is introduced into the AHU through the mixing box. Air is passed over parallel heating and cooling coils to a linked set of zone dampers (two per zone, one for the hot deck, and the other for the cold deck). Each deck discharge temperature is maintained by a control valve tied to the deck discharge temperature sensor. As the command for zone cooling increases, the cold deck damper opens and the hot deck closes in proportion to maintain a constant airflow to the zone.

2.2 Bypass / Cold Deck with Zone Reheat (Texas multizone)

Return air is introduced into the AHU through the mixing box. Air is passed over the cooling coil and an equal bypass section to a linked set of zone dampers (two per zone, one for the cold deck, and the other for the bypass). The cold deck discharge temperature is maintained by a control valve tied to the deck discharge temperature sensor. As the command for zone cooling increases, the cold deck damper opens and the bypass deck closes in proportion to maintain a constant airflow to the zone. If space heating is required a reheat coil for each zone is located downstream of the zone dampers.

2.3 Hot Deck / Bypass / Cold Deck (Three-deck multizone)

Return air is introduced into the AHU through the mixing box. Air is passed over parallel heating and cooling coils and an additional bypass to a linked set of zone dampers (two per zone, one for the hot deck-bypass, and the other for the cold deck-bypass). The hot and cold deck discharge temperatures are maintained by a control valve tied to the deck discharge temperature sensor for each coil. As the command for zone cooling increases, the cold deck damper opens and connected bypass closes. As the demand for zone heating increases, the hot deck opens and connected bypass damper closes.

3 GENERAL INSTRUCTIONS TO THE DESGNER

The specifications listed on Drawing Sheet M-103, Specifications serve as a template for the designer in communicating their design intent for the project. Currently there are two major sections shown in the specifications:

- Variable Frequency Drives
- Controls System and Instrumentation

More sections may be required/added at the designer's discretion. Selections are shown in square brackets [ ] to assist with text search and replace functions.

4 VARIABLE FREQUENCY DRIVES

4.1 Re-use Existing Motors vs Replacement

DESIGNER NOTE: Determine if the existing motor is suitable for operation with a VFD and will therefore be reused. If a new motor is required, use the first bracketed sentences in paragraph 2.1.1 and delete the second bracketed sentences. If the existing motor is reused, delete the first bracketed sentence and use the second.

There does not appear to be a standard definition for "inverter-duty" motors, and terms such as "inverter-ready" also have different meanings among motor manufacturers. The selection of a motor for this type of application should be made using the National Electrical Manufacturers Association (NEMA) MG1 Part 31 (Definite-Purpose Inverter-Fed Polyphase Motors). In general, the VFD HVAC motor application does not appear to require a top-of-the-line "inverter-duty" motor. Inverter-duty motors are very expensive, typically 3 to 4 times the cost of a premium efficiency motor. Premium-efficiency motors often carry the designation "inverter-ready" or "inverter-friendly," and may meet the NEMA requirements for HVAC applications. The general recommendation for the VFD and motor is to specify a premium-efficiency motor that meets NEMA requirements and a drive from the same supplier, to obtain a coupled set that is intended to function as a unit.

4.2 Fan Pulleys & Belts

DESIGNER NOTE: Determine the condition of the fan drive pulleys and edit the paragraph below accordingly.

Suggested Subsections to review:

2.3 Pulleys and Belts

2.3.1 [Provide new motor and fan pulleys.] [Reuse existing motor and fan pulleys.]

4.3 DDC Integration

DESIGNER NOTE: The design intent is to have all control input/output points hardwired to the VFD including but not limited to:

- Fan Start/Stop
- Fan Status
- Fan Speed Command
- VFD Faulty Status

In some cases, the owner and designer may want to integrate the VFD through a communications card option on the VFD. The addition of the communications card provides substantially more information about the status and operation of the drive. While this information may be beneficial, the designer is encouraged to keep the control and monitoring points mentioned above as hardwired points.

Suggested Subsections to review:

2.2.1 [LonWorks TP/FT-10 and provide nvi (network variable input) and nvo (network variable output) SNVTs (Standard Network Variable Types)][BACnet using ASHRAE 135 Input/Output Objects]

5 CONTROL SYSTEM & INSTRUMENTATION

5.1 Direct Digital Controls

DESIGNER NOTE: Determine what devices require replacement or re-use. If there is a DDC system in place consider the re-use of existing devices, wiring, conduit and control panels to provide a benefit to the owner by reducing the installation cost.

Suggested Subsections to review:

1.1.1 The control system must be an [extension of the existing control system][open implementation of LonWorks technology using CEA-709.1-C as the communications protocol and using LonMark Standard Network Variable Types as defined in LonMark SNVT List][open implementation of BACnet technology using ASHRAE 135 as the communications protocol and using standard ASHRAE 135 Input/Output Objects.

2.3 DIRECT DIGITAL CONTROL (DDC) HARDWARE.

2.3.1 General Requirements. All DDC Hardware must meet [UFGS 23 09 23.01 – Lonworks Direct Digital Control for HVAC and other Building Control Systems] [UFGS 23 09 23.02 – BACnet Direct Digital Control for HVAC and other Building Automation Systems][INSERT Currently Installed Direct Digital Control System Specification]

5.2 Temperature Sensors

DESIGNER NOTE: Consideration should be given to the type of temperature sensors used. Room temperature sensor functionality (display, setpoint adjust, night setback override) as well as combination sensors (humidity, carbon dioxide, occupancy) should be used where applicable and desired by the local facility. RH sensors should only be used in systems with reheat capability. CO2 sensors should only be used in applications with demand controlled ventilation capability.

Duct Probe Sensors should be used where space is limited (zone discharge air temperatures) and where air stratification is not an issue.

Duct Averaging Sensors should be used where air stratification is a concern (mixed air sensors). Adequate space and access should be maintained for proper installation and maintenance.

Outside Air Sensors should be located in the proper location with the appropriate weathershield and be located away from exhaust airstreams.

Zone Discharge Air Sensors are highly recommend as they are a very inexpensive diagnostic/troubleshooting tool if there are available controller inputs.

Suggested Subsections to review:

2.2.1.3 Temperature Sensor Details.

a. Room Type: Provide the sensing element components within a decorative protective cover suitable for surrounding decor. [Provide temperature sensors including options as shown][Provide room temperature sensors with timed override button, setpoint adjustment lever, digital temperature display.]

5.3 Air Flow Measurement Station (Array)

DESIGNER NOTE: Air Flow Measuring Stations (Arrays) should be considered in applications where minimum airflow levels are desired. Two typical styles of AFMAs are used.

- Pitot Tube Style. Less expensive but require a minimum velocity of 400 feet/minute velocity for stable measurement. Some manufacturers say they can read at lower velocities but care should be exercised when selecting these units.
- Electronic Style. More expensive and can read at lower velocities. Should be used in applications where the outside air duct is sized for full AHU fan capacity (economizer capability).

Airflow straighteners may be required depending upon the availability of adequate entering ductwork straight run prior to the station. Consult with the manufacturer of the preferred basis of design to determine if straighteners are needed.

For locations where outside air temperatures are extreme, exercise care in specifying AFMAs that can operate under the full range of expected temperatures.

Suggested Subsections to review:

2.2.3.1 Airflow Measurement Array (AFMA).

c. Outside air temperature. In outside air measurement or in low-temperature air delivery applications, the AFMA must be certified by the manufacturer to be accurate as specified over a temperature range of [-20 to +120 degrees F] [_____].

5.4 Filter Status Monitoring

DESIGNER NOTE: The need for filter status monitoring has declined due to most operational organizations transition to maintaining filters on a fixed schedule. The designer should confirm with the local maintenance and operations staff to determine the project requirements. The filter status switches should be an adjustable differential pressure switch that will automatically reset.

Suggested Subsections to review:

2.2.2 Differential Pressure Instrumentation

2.2.2.1 Differential Pressure Switch

The switch must have a field adjustable setpoint. The device must be sized for the application such that the setpoint is between 25 percent and 75 percent of the full range. The over pressure rating must be a minimum of 150 percent of the highest design pressure of either input to the sensor. The switch must have two sets of contacts and each contact must have a rating greater than its connected load.

6 SEQUENCES OF OPERATION

6.1 Outside Air Flow Control

The pre-existing constant volume system will likely use fixed damper position for outside air flow control. Conversion to variable volume will require use of an outside air flow control scheme. The template sequence includes three options from which to choose and each calls for specification and installation of an outside air flow measurement station.

6.2 Outside Air (Mixing Box) and Relief Control

DESIGNER NOTE: There may be only one analog (modulating) output for the outdoor air damper (or mixing box damper, OA + RA). The design intention is to modulate the outside air (OA), return air (RA), and relief air (RLA) dampers in unison. The designer is encouraged to accommodate require specify a separate analog output (AO) and separate actuators for each of the three dampers. Note that there are individual AOs in the points list for each of these dampers. This allows flexibility to adjust damper positions as needed for flow control. For minimum OA control, the Relief Air Damper should not need to be opened unless the OA requirement for the space significantly exceeds the exhaust and pressurization requirements. For economizer mode, at a minimum, the relief air damper command should be slightly offset (closed) relative to the RA damper to make sure OA is not being pulled into the building through the Relief Air Duct. This is especially important if there is no return fan or relief fan in the mix and the system is relying on duct static pressures at the relief air plenum and mixing box. Some designers use a space static pressure sensor, others use relief plenum pressure to control the damper position. A third way is to measure the flows (& pressures) during TAB when the AHU fan is at max flow and min flow to determine the min and max position for the relief damper during economizer. This application requires a designer and TAB contractor to work in unison during setup. If this effort is desired, make sure there is language in the PWS to require this coordination.

6.3 Linked vs Unlinked Hot-Deck/Cold Deck Zone Control

DESIGNER NOTE: Breaking the link between the zone hot-deck/cold-deck dampers is an unlikely but potential application for the MZ-VAV conversion. The premise of even greater fan energy savings is under consideration but has not been proven as of the publish date of this design guide.

If unlinking the damper connecting links is to be attempted (upon verification this is possible), separate hot and cold deck actuators and ZN-HD-C and ZN-CD-C signals are required on the Control Schematic and Points Schedule.

7 OTHER REQUIREMENTS

7.1 Damper Position Feedback Option

DESIGNER NOTE: Zone Damper Position feedback (ZN-D-POS) is an option that is readily available on damper actuators (in some cases at an additional cost). The larger cost impact is on the increased point count on the DDC controller requiring a larger plant controller especially when combined with the zone discharge temperature sensors. If space is not available for both damper position and zone temperature sensors, the designer is encouraged to choose the zone temperature sensors as they are a better troubleshooting/diagnostic tool for the investment.

7.2 Test, Adjust and Balance (TAB)

DESIGNER NOTE: TAB of the renovated AHU and associated distribution system may or may not be required. Consider it if the space airflow requirements have changed since the original installation or if there are significant airflow changes due to outside air requirements or sequence modifications (demand controlled ventilation, economizer capability, etc.).

7.3 Fire Alarm System (FAS) Coordination

DESIGNER NOTE: Determine if both supply and return air smoke detectors are needed and what they should signal. The control schematic default is that a FAS shutdown relay is connected to the VFD. Most integrated FAS are microprocessor based with all smoke detectors, pull stations, etc. reporting back to a FACP. Individual shutdown relays should be within 1 meter of each controlling device (starter, VFD, etc.) that disables the fan. There are some instances of hardwired smoke detectors to the fan controlling device but they are becoming the exception rather than the rule. If there is an exception that the smoke detector is to be directly interlocked with the controlling device, then the specifier should resolve.

7.4 Performance Work Statement Coordination

References are made to the Performance Work Statement in PART 2 – Products. The PWS will be the contractual mechanism to implement the design intent. As such, the clarity and detail of the PWS will greatly impact the quality and cost of the project. The PWS would be the best mechanism to tailor the requirements of the particular installation. The Designer can list the referenced UFGS & UFCs as well as any other requirements (local design requirements, TAB effort, etc.).